



**A NUMERICAL SCHEME FOR PREDICTING
TRANSIENT SHOCK, BOUNDARY LAYER, AND
MAGNETOHYDRODYNAMIC PHENOMENA**

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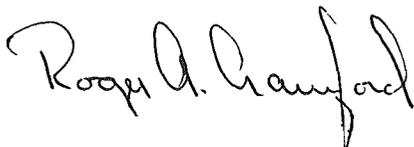
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<p>A stable procedure of first order accuracy for solving the coupled axisymmetric transient gasdynamic and electromagnetic equations is presented. A numerical integration technique developed by Matuska for inviscid flow is extended to include viscous and electromagnetic terms with stability, convergence and computational speed comparing favorably with other existing hydrocodes. In this investigation, the method is applied to a number of transient hydrodynamic and magnetohydrodynamic applications characterized by</p>																						

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20. ABSTRACT (Continued)

by the interaction of gasdynamic, electromagnetic and viscous flow phenomena.

The external flow field around an M-117 warhead, an ablating reentry vehicle and a semi-infinite circular cylinder, and the internal flow of a nozzle, shock tube and MHD channel is examined under viscous and inviscid conditions. Attention is focused on the behavior of a conducting fluid in the presence of shocks, boundary layers, heat transfer and electromagnetic fields. Finally, the investigation of an MHD generator is described with emphasis placed on aerodynamic and viscous effects influencing the behavior of the energy conversion process. Results of these calculations are shown to be in close agreement with experiment and other theoretical solutions.

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PREFACE

The work reported herein was conducted by the author during periods of Air Reserve active duty at the Arnold Engineering Development Center, Air Force Systems Command under Program Element 65807F and while a graduate student at Auburn University, Auburn, Alabama. The effort was also supported in part by the University of Tennessee Space Institute, Tullahoma, Tennessee and by the Armament Development and Test Center, Eglin AFB, Florida under Project No. 9991VX13.

AEDC Project Managers were Lt Col J. R. Roland and Lt Col R. A. Crawford; Capt K. L. Kushman served as technical advisor.

With the exception of Appendix C, this report was presented as a dissertation in partial fulfillment of the requirements for a Doctor of Philosophy degree at Auburn University in June 1978 and was published as a thesis. That thesis was copyrighted by the author, Capt Laurence A. Feldman. The copyright holder has granted the Government a royalty-free unlimited license to use, duplicate, or disclose copyrighted material in whole or in part and to permit others to do so.

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I. INTRODUCTION

Finite integration techniques are commonly employed to numerically solve mathematical models of physical problems, when the essential features of the model preclude exact analytic solutions. Nayfeh (1) points out that these features include nonlinearities, variable coefficients, complex boundary shapes and nonlinear boundary conditions at known or, in some cases, unknown boundaries. In the case of magnetohydrodynamics or gasdynamics, all of the above undesirable features exist and must be treated.

The primary objective of this dissertation is to solve the viscous gasdynamic and electromagnetic equations of motion in their most fundamental form. The numerical approach selected is finite differencing. Naturally, a numerical solution to these complex and highly nonlinear coupled partial differential equations will place the greatest burden on the computer; however, when considering the futility of employing other non-discretized approaches to meeting the same objective the demands placed on the computer become less significant.

1.1 Motivation

The need for investigating the behavior of a conducting fluid, both experimentally and theoretically, has been well established over the past few decades. However, a review of the literature relevant

to magnetohydrodynamic technology (Section 1.2) reveals that the progress by computational magnetohydrodynamicists has been somewhat limited.

The major obstacles to the development of a numerical approach for solving the equations which govern MHD flow were:

- (1) small and slow computers unable to accommodate the demands of most numerical integration techniques; and
- (2) a lack of accurate and converging finite difference schemes describing the equations governing MHD phenomena.

The primary objective of this dissertation is to develop a numerical procedure for investigating the complex and highly nonlinear hydrodynamic, viscous and electromagnetic behavior of a conducting fluid. Emphasis was placed on the transient coupling between the gasdynamic and electromagnetic fields. A two-dimensional finite difference technique was developed to model the transient behavior of this fluid.

Traditional methods for solving inviscid or viscous problems such as the method of characteristics (hyperbolic system) or similarity solution and asymptotic expansions suffer from a lack of generality and are restricted by limiting assumptions, neglected terms and inexact linearization of the original governing equations. Further, shocks or subsonic/supersonic regions have to be treated separately and create problems associated with matching solutions derived by different methods as well as cumbersome bookkeeping in satisfying the Rankine-Hugoniot relations across the shock. If the viscous and inviscid calculations are performed separately, a priori information is required as the exact location of the boundary separating the two regions and may lead to inconsistencies if improperly matched.

A discretization approach to the equations of motion in the form of finite difference expressions has significant advantages over the previously mentioned techniques. Namely, this method is consistent throughout all flight regimes, subsonic through hypersonic, and treats the viscous and inviscid regions in identical fashion. The time-dependent problem is considered where some initial set of conditions are imposed and the steady-state solution is generated as the limiting case. Shocks or discontinuities* develop naturally from imposed boundary conditions and the Rankine-Hugoniot equations are automatically satisfied as would be expected since they are expressions of the conservation equations approximated by finite difference terms. Nonlinear terms present no additional complexity if treated explicitly (Section 1.3) even when property values are a function of state values. The interaction of gas dynamic and electromagnetic fields is numerically treated simultaneously and eliminates the need for solving each independently and then iterating both fields to a compatible and converging solution.

Dealing directly with the equations of motion through the finite difference equations, the hydrodynamicist becomes a spectator** to the influence of the physical laws of nature on the dynamic behavior of fluids as opposed to other techniques where the physical processes are obscured by mathematical abstractions, substitutions and approximations.

*"Numerical diffusion" is inherent in all discretization methods and tends to spread or smear discontinuities over at least two cells. Although the shock thickness is unrealistic, the jump conditions before and after the shock are quite accurate.

**Employing adequate computer graphics (vector, contour, shading plots; computer movies), the user "observes" the occurrence of the phenomenon without having to resort to cumbersome data reduction and analysis.

The primary disadvantage of hydrocodes* is that the numerical procedure is costly in computer time and in some cases computer storage.

Analytic investigations reduces a physical phenomenon to a set of mathematical equations with appropriate boundary and/or initial conditions. The MHD generator problem is composed of many interacting phenomena, each of which if treated independently would constitute significant mathematical problems in the areas of thermodynamics, heat transfer, boundary layer theory, electromagnetism, aerodynamics, fluid mechanics and energy conversion. The MHD generator problem was chosen because it not only represents one of the more severe challenges to a finite difference technique, but the results of such a program would also benefit the progress made in MHD power technology.

1.2 Previous Calculations

Although the past two decades have seen progress in the development of magnetohydrodynamic technology mostly through experimentation, analytic models developed since 1957 have contributed in varying degrees to present understanding of the interaction between gasdynamic and electromagnetic forces. Initially, attention was focused on MHD accelerators with interest directed toward aerospace or military application. More recently, interest has centered on the use of MHD power generators to increase the efficiency of extracting energy from natural resources.

The performance of an MHD generator in converting thermal/kinetic energy into electrical energy is significantly influenced by thermo-

*A finite difference computer program solving the inviscid equations of motion.

dynamic/hydrodynamic effects of: compressibility, viscosity, shocks, heat transfer, non-scalar conductivity and Hall current in addition to electrode and material performance and such design aspects as size, configuration and geometry. Accurate modeling of a generator must take into account the above phenomenon.

The fundamental difficulty in developing a computational model for predicting magnetohydrodynamic phenomena is the coupling of equations governing both the gas dynamic flow and the electromagnetic (EM) fields. Since the flow fields affect the EM fields and vice-versa, the non-linear partial differential equations must be solved simultaneously and stability and convergence of the solutions become greatly complicated (Figure 1).

Approaches to solving MHD problems have consisted of the following:

- (A) One-dimensional "influence coefficients,"
- (B) One-dimensional closed form analytic solutions to ordinary differential equations.
- (C) Similarity transformation and closed form solutions to a modified differential equation in one or two dimensions.
- (D) One-, two-, and three-dimensional numerical solution to the uncoupled steady MHD equations.
- (E) One-, two-, and three-dimensional numerical solution to the coupled steady MHD equations using either the magnetic induction equation or the elliptic equation governing the electric fields and currents.
- (F) One-, two-, and three-dimensional transient numerical solution to the coupled MHD equations using either the magnetic induction equation or the elliptic equation.

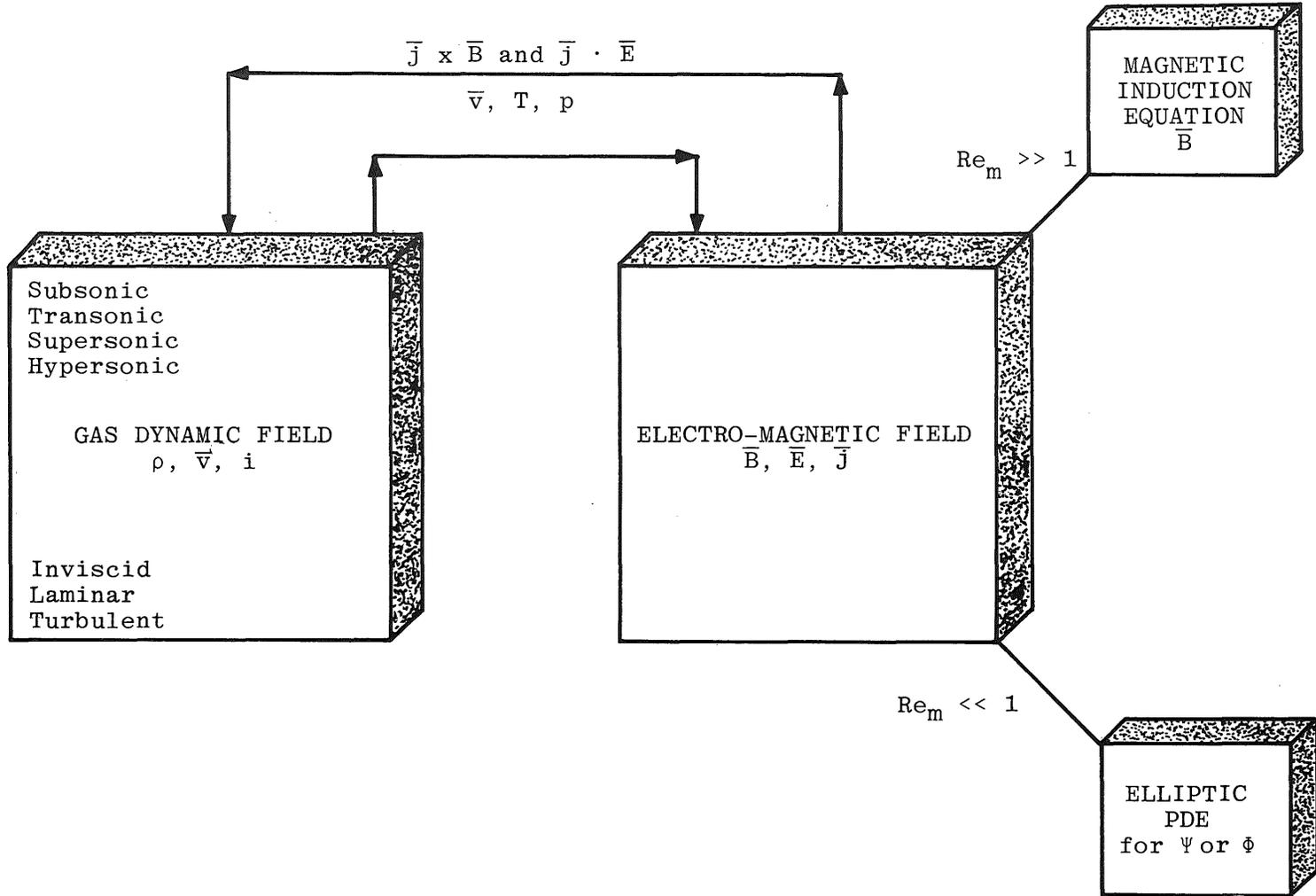


Fig. 1 Flow Diagram of Gas Dynamic-Electromagnetic Coupling

Methods (A), (B) and (C) are exact but are restricted to a narrow range of problems. Approaches (D) and (E) provide rapid convergence to a steady state solution but do not consider the transient behavior between the gas dynamic and electromagnetic fields, or sometimes the strong coupling between the two sets of fields. The last method, (F), is desirable since it treats a wide range of problems, it suffers, however, from large computational times.

A literature survey was performed on the subject of "theoretical modeling of MHD calculations" and is presented in six subsections: (1) hydrocodes; (2) MHD hydrocodes; (3) MHD boundary layers; (4) electric potential and current stream functions; (5) MHD shocks; and (6) simplified MHD analysis.

Hydrocodes

There are at present hundreds of existing hydrodynamic computer programs commonly referred to as "hydrocodes" as discussed in Section 1.3. They are categorized as either Eulerian or Lagrangian, explicit or implicit, viscous or inviscid, etc. The origin of these programs can be traced to less than a half dozen sources and although each hydrocode has been tailored by its own evolutionary process, the fundamental nature of all codes can be categorized into a small class of finite difference techniques. This is not to imply that the stability or convergence or rate of convergence of these programs are equivalent; some programs remain stable and give accurate solutions for a limited

number of problems over a restricted integration region, whereas other methods can treat a wider variety of problems under more severe numerical conditions.

Pioneers in the field of hydrocodes can be traced to those organizations equipped with the most advanced computer systems. Some leading theoreticians (2-4) began work in the late 1940's which resulted in the development of hydrocodes beginning in the early 1950's (5-17). Numerous authors (18-20) have made comparisons of these finite difference techniques.

MHD Hydrocodes

A number of MHD hydrocodes exist with the predominant number employing implicit schemes and solving the magnetic induction equation instead of the elliptic equation describing the stream function or potential. Roberts and Potter(21) and Killeen (22) discuss finite difference equations and MHD hydrocode applications. In 1963, Roberts, et al., (23) developed "THETATRON," employing the magnetic induction equation, designed to treat plasma problems such as "theta pinch containment." Freeman and Lane (24) developed in 1969 an explicit, Eulerian, Lax-Wendroff MHD technique. Two-dimensional laminar compressible MHD flow problems were treated by Fritzer, et al., (25) in 1972. Eddy currents were calculated using a modified FLIC (Fluid In Cell), PLIC (Plasma In Cell) and employing the donor-receiver technique (see Appendix A.1). It was found that since the ratio of the speed of light to sound was many orders of magnitude, the induction equation had to be solved at this same ratio for each gas dynamic time iteration. It was determined that gradients of velocity, conductivity

and magnetic field can tailor the shape of stream currents in a desired fashion.

Other techniques were developed (26-29) for plasmas which solve the magnetic induction equation. Fajen (26) in 1973 used the Harlow and Amsden "ICE" code and modified it to a Lax-Wendroff scheme. Brackbill and Pracht (27) in 1973 extended the "ICE-ALE" technique into an "almost-Lagrangian" (11) implicit scheme. Gubarev (30) in 1973 employed the assumption of small magnetic Reynolds number and investigated the stagnation of supersonic flow of a conducting gas in an MHD channel with Hall currents. One electrode was considered. In 1974 Ostretsov (31) divided the system into two subsystems, one containing the equations describing the EM fields and the other describing the gas dynamics, and constructed an iteration scheme between the two. Lindemuth (29) in 1974 employed an alternating direction implicit scheme to treat plasmas of high magnetic Reynolds numbers. Bakhrakh and Gubkov (32) used a 2-D axisymmetric finite difference method with finite conductivity and an azimuthal magnetic field. The solution was developed in three phases: (1) computing the hydrodynamics, while freezing the magnetic flux, (2) while freezing the fluid dynamic state, computing the induced magnetic field, and (3) computing Joule heating. It was determined that the order in which these three phases were carried out did not affect the final results.

MHD Boundary Layers

In the late 1950's, Rossow and Bush (33-35) studied the interaction of a conducting, viscous fluid with an applied magnetic field. It was found that the drag, skin friction and heat transfer were affected by

the strength of the magnetic field which in turn could be exploited to control the motion of a fluid. Sherman (36) in 1961 studied the influence of a nonuniform magnetic field on a Blasius boundary layer. Others including Sears, Hunter, Wu, Taylor, Denzel, High and Felderman (37-40) studied the effects of nonuniform properties of an equilibrium plasma in a segmented MHD generator assuming laminar or turbulent velocity profiles. Dix and Dukowicz (41,42) considered a solution to the equations of motion for flow over a flat plate boundary layer under the influence of a transverse magnetic field for low magnetic Reynolds number. Monis, Eustis, Krueger and Self (43) in 1973 matched a 1-D gas dynamic solution with a 1-D boundary layer solution under the influence of a magnetic field. Doss, Dwyer and Hoffman (44) investigated compressible laminar and turbulent boundary layers in an MHD channel. Also in 1973, Derkach and Zhigula (45) developed a closed form analytic solution to flow over a long cylinder under a radial magnetic field. The work of Demetriades, Argyropoulos and Maxwell (46) consider two- and three-dimensional solutions to viscous flow in MHD generators and accelerators.

Electric Potential and Current Stream Functions

The 2-D Laplace equation of the electric potential or the current stream function, discussed in Section (2), was solved initially by conformal mapping (47-51). End effects, variable geometry and concentration of current resulting from Hall current around electrodes were investigated. Dzung (52) in 1962 employed a series solution, whereas Sherman (53) considered conductivity a function of current and developed a solution using an expansion technique. More recently,

Poberenzhskii and Yakkot (54) employed an analytic solution using the method of images of vortex source combinations. Crown (55) was the first to attempt a numerical relaxation technique but developed numerical instabilities for Hall parameters greater than 2. Celinski and Fischer (56) in 1966 eliminated this numerical problem by modifying the numerical technique and calculated solutions with Hall parameters up to 10. Louis, Lothrop and Brogan (57) used simple theories for flow with uniform properties and predicted fluctuations of current distribution in time and space, particularly near electrodes. Finally, Oliver (58) considered instabilities due to spatial nonuniformities in the electrical conductivity from inhomogeneous mixing of ionizable species, resulting from variable fluid properties or nonuniform Joulean heating. Relaxation techniques were employed to investigate these instabilities.

MHD Shocks

There are numerous papers concerning MHD shocks and Alfvén waves. Some analytic expressions for MHD shocks were developed by Greifinger and Cole (59) and Natter (60). Numerical calculations were performed by Chu and Taussig (61), Sutton and Sherman (62), and Shank and Morse (63), the latter two employing the "Particle In Cell" method developed by Harlow, et al. The use of magnetic fields to displace shocks on re-entry vehicles was discussed by Resler and Sears (64) and Ziemer (65) in their papers concerning the prospects of "magnetoaerodynamics."

Simplified MHD Analysis

Other MHD analysis included the work of Sutton (66) in 1959 who discussed the relationships which govern the performance of constant

velocity, temperature, pressure, density and area generators, whereas Swift-Hook (67) considered a constant temperature generator. MHD flow parameters were studied by Wilson, et al., (68) by employing 1-D influence coefficients which governed the behavior of the fluid under pressure, temperature, friction area change and Lorentz force terms. Similarly, Zampaglione (69) considered choking in a constant area channel and Chubb (70) studied an MHD nozzle.

One-dimensional analysis of MHD flow was investigated by Neuringer (71) using the method of calculus of variation in seeking conditions for optimum power generation. Brocher (72) and Blecher (73) studied in 1961 a constant velocity MHD generator with variable conductivity and developed closed form expressions yielding generator performance. Ralph and Harwell (74) in their discussion of power and performance of MHD generators determined that since power is proportional to conductivity times velocity squared, an optimum ratio of internal to kinetic energy will yield an optimum Mach number resulting in optimum power.

Other studies include the work of Sonnerup (75), Roy and Wu (76) and Sherman and Sutton (77), who considered incompressible constant property 2-D flow under the influence of a tensor conductivity and segmented electrodes.

The performance of MHD generators was also investigated by others (78-87); those investigators considered the adverse influence of boundary layers (laminar and turbulent), Hall current, separation, end effects, external loading and geometry on the power and efficiency of generators.

1.3 Fundamentals of Numerical Methods

This dissertation illustrates the stability and, where practical, the convergence and compatability of a numerical technique to be subsequently described through application to a number of problems outlined in Section 1.4.*

A method is called stable if any bounded starting procedure yields a uniformly bounded solution of the difference equation as the step size goes to zero. A method is converging if the values of the solution to the finite difference equations (FDEs) approximating the differential equation tend to the values of the exact solution to the differential equation. Finally a method is compatible if the truncation error goes to zero as the step size goes to zero (88). Thus, if a method is stable, converging and compatible, the solution to the finite difference equations is bounded, its error is influenced by the step size and the differential equation solved by the FDEs is indeed the differential equation under investigation.

If a finite difference technique is used to approximate a set of equations, it is characterized by the time and space coordinate systems employed. A coordinate system fixed to the moving fluid (constant mass) is known as "Lagrangian," whereas a coordinate system fixed in space (constant volume) is categorized as "Eulerian." If the time derivative of variable f is evaluated based on values of f at other locations, also being simultaneously evaluated, the method is

*A rigorous mathematical stability analysis was not performed.

referred to as "implicit," whereas if the time derivative of variable f is evaluated based on values of f at other locations and these values are already known from a previous time, the method is identified as "explicit." The basic advantages and disadvantages of the Lagrangian, Eulerian, implicit and explicit methods are outlined below. The convenience in treating boundary conditions and grid distortion play major roles in the selection of the method employed.

Given a partial differential equation such as:

$$\frac{d}{dt}(u) = L(u) \quad (1)$$

where L is a differential operator with independent space coordinates, the integration of u may be performed by two methods: explicit or implicit

where

$$\int \frac{d}{dt}(u) dt = \int L(u) dt \quad (2)$$

$$u_{i,j}^{n+1} - u_{i,j}^n = \epsilon \Delta t L^{n+1}(u_{i,j}^{n+1}) + (1-\epsilon) \Delta t L^n(u_{i,j}^n) \quad (3)$$

$$\Delta t = t^{n+1} - t^n \quad (4)$$

and ϵ = integration parameter; explicit = (0), implicit = (1). If $\epsilon = 0$,

$$u_{i,j}^{n+1} = u_{i,j}^n + \Delta t L^n(u_{i,j}^n) \quad (5)$$

The explicit calculation provides values for u at time $(n+1)$ based on values of u at time (n) , which are obviously all known. However, numerical stability for an explicit technique restricts the time step, and thus the rate of convergence to a steady state solution.

A discussion of the stability criteria follows, but its physical interpretation suggests that, "The rate of propagation of information by the finite difference solution across a mesh cannot exceed one space-step during each time-step and must be able to keep up with all propagation speeds of the differential system, including waves, fluid motion and diffusion." (21) The most unfavorable local case (smallest cell, largest signal velocity) must necessarily be taken.

If $\varepsilon = 1$,

$$u_{i,j}^{n+1} = u_{i,j}^n + \Delta t L^{n+1}(u_{i,j}^{n+1}) \quad (6)$$

and the implicit integration computes u at time $(n+1)$ based on neighboring values of u also at time $(n+1)$ which are not known. If the L operator is linear, then the solution to the equations has been reduced to the solution of a set of simultaneous algebraic equations at each time step. The matrix is tri-diagonal and can expeditiously be inverted algebraically (3).

In the former explicit case, all terms on the rhs are known, and each updated value of u is individually computed. In the latter implicit case, values on the rhs of the FDE are not known and values for the neighboring points must be computed simultaneously by either matrix inversion, if the equations are linear, or some iteration procedure, if the equations are nonlinear.

Although the time interval of an implicit calculation is not restricted by the speed at which signals propagate (primarily the local speed of sound), it is regulated by the particle velocity and cell size. Since the computation time for an implicit time step calculation is four

to five times greater than that for the explicit calculation, problems where the flow field has speeds in excess of Mach 0.2 to 0.25 will be more efficiently computed explicitly. Also, representing the FDEs in the form of simultaneous algebraic equations which may be cast in the traditional tri-diagonal matrix, nonlinear terms must be either ignored or treated explicitly. Thus implicit programs work most efficiently for incompressible linear problems and compare unfavorably at high subsonic speeds.

Many existing hydrocodes claim to be able to solve the transient "initial value problem" (IVP) when in actuality their methods are efficient only for the steady state "boundary value problem" (BVP). In solving the BVP, a unique solution exists for a prescribed set of boundary conditions, providing that these boundary conditions are not time-dependent. The steady state solution is developed by relaxing to the final state from some arbitrary set of initial conditions. Relaxation does not connote solving the transient equations as may be incorrectly assumed. Implicit programs converge to the steady state solution more rapidly than explicit programs because of the more stringent stability criteria plaguing the explicit method. However, for the IVP, where transient behavior is considered, implicit programs are not competitive because either large time steps as employed in the BVP will result in a grossly inaccurate transient solution or smaller time steps yields a more expensive calculation when compared with the explicit approach. In a complex problem, where such phenomena as shocks reflecting or interacting with boundary layers occur over a period of microseconds, one cannot expect much fruition from a calculation which "smears" this

behavior over a time step of milliseconds. It is therefore emphasized that "pseudo-transient" implicit techniques which do not violate any stability criteria do not necessarily converge.

In the explicit scheme, since the new value of the dependent variable is based on the old value of its neighbors, a large step size, or one that exceeds a stability bound, can obviously lead to an instability because the change may be unrestrained. In the implicit scheme, however, since the new value of the dependent variable is based on the new value of its neighbors, all values of the dependent variable (including boundary values) are implicitly "tied" to each other and serve as a restoring or restraining force on the behavior of the dependent variable in ensuing iterations. Although the implicit scheme is stable usually under the severest of conditions (large step size, high nonlinearity, etc.) the accuracy of its solutions will suffer significantly if controls are not placed on the step size.

A basic problem in solving the equations governing MHD flow is the simultaneous treatment of numerous physical processes: magnetic, thermal, viscous transport, hydrostatic compression, etc. Starting with known initial conditions in density, velocity, energy and magnetic induction (or electric potential or stream current), the transient response of a fluid under prescribed boundary conditions is computed at selected time intervals. These intervals, although desired large in order to minimize computational time, are unfortunately for an explicit scheme strongly dictated by some basic stability criteria which implicitly expresses the speed of a signal of some wave or diffusive phenomenon. Lagrangian integration (fixed mass) is significantly influenced by

advective terms in the governing equations. "The transport of physical variables such as density, temperature, magnetic field and velocity from point to point by the bulk motion of the fluid is represented by $\bar{v} \cdot \nabla$ terms. Superimposed on these terms are other kinematic effects such as adiabatic compression or diffusion. Clearly a Lagrangian formulation using a mesh which moves with the fluid can transform away the bulk motion altogether allowing the remaining terms to be treated more accurately." (3) If however, the convective terms dominate, then the grid frozen to the mass becomes severely distorted and results in large discretization error. Rezoning the mesh, periodically, can result in large conservation errors. "A fixed Eulerian mesh is normally used in practice and thus requires careful treatment of the advective (convective) term if physical diffusion is not to be masked by numerical effects." (Ref. 3)

The time step over which each integration (cycle) is performed is governed by stability criteria.

Stability conditions which control the time step Δt are:

(A) The Courant condition:

$$\frac{\Delta z}{\Delta t} > c ; \frac{\Delta r}{\Delta t} > c \quad (7)$$

(B) The particle velocity condition:

$$\frac{\Delta z}{\Delta t} > u ; \frac{\Delta r}{\Delta t} > v \quad (8)$$

which prohibits the transmission of a signal or mass across more than one cell in one time interval.

(C) Viscosity condition:

$$\frac{2}{3} \frac{\mu}{\rho(\Delta z)^2} < \frac{1}{\Delta t} ; \frac{2}{3} \frac{\mu}{\rho(\Delta r)^2} < \frac{1}{\Delta t} \quad (9)$$

$$\frac{\mu_E}{\rho(\Delta z)^2} < \frac{1}{\Delta t} ; \frac{\mu_E}{\rho(\Delta r)^2} < \frac{1}{\Delta t} \quad (10)$$

(D) Alfven condition:

$$\frac{1}{\Delta r} \frac{B^2}{\mu_p \rho} < \frac{1}{\Delta t} ; \frac{1}{\Delta z} \frac{B^2}{\mu_p \rho} < \frac{1}{\Delta t} \quad (11)$$

Employed in conjunction with the solution of the magnetic induction equation which prohibits the transmission of an Alfven wave across more than one cell in one time interval.

(E) Thermal conductivity condition:

$$\frac{\lambda}{\rho c_p (\Delta z)^2} < \frac{1}{\Delta t} ; \frac{\lambda}{\rho c_p (\Delta r)^2} < \frac{1}{\Delta t} : \text{laminar} \quad (12)$$

$$\frac{\lambda_t}{\rho c_p (\Delta t)^2} < \frac{1}{\Delta t} ; \frac{\lambda_t}{\rho c_p (\Delta r)^2} < \frac{1}{\Delta t} : \text{turbulent} \quad (13)$$

(F) Magnetic diffusion condition:

$$\frac{1}{\sigma_{\mu_p} (\Delta z)^2} < \frac{1}{\Delta t} ; \frac{1}{\sigma_{\mu_p} (\Delta r)^2} < \frac{1}{\Delta t} \quad (14)$$

(G) Lorentz condition:

$$\frac{\sigma B^2}{\rho} < \frac{1}{\Delta t} \quad (15)$$

Considering all phenomena, the time step becomes:

$$\Delta t = \Delta z / \left\{ u + c + \frac{2}{3} \frac{\mu}{\rho \Delta z} + \frac{\mu_e}{\rho \Delta z} + \frac{B^2}{\rho \mu_p} \Delta z + \frac{\lambda + \lambda_T}{\rho c_p \Delta z} + \frac{1}{\sigma \mu_p \Delta z} + \frac{\sigma B^2}{\rho} \Delta z \right\} \quad (16)$$

$$\Delta t = \Delta r / \left\{ v + c + \frac{2}{3} \frac{\mu}{\rho \Delta r} + \frac{\mu_e}{\rho \Delta r} + \frac{B^2}{\rho \mu_p} \Delta r + \frac{\lambda + \lambda_T}{\rho c_p \Delta r} + \frac{1}{\sigma \mu_p \Delta r} + \frac{\sigma B^2}{\rho} \Delta r \right\} \quad (17)$$

where Δt is evaluated at each cell and the minimum value employed.

1.4 Scope of Present Work

The objective of this investigation is to demonstrate a numerical procedure which can predict the transient aerodynamic behavior of a (conducting) fluid under the influence of viscous and/or electromagnetic forces. Calculations are performed in two-dimensions (axisymmetric), although the technique can be easily expanded to treat three-dimensional flow. Further, although variations in the grid formation or integration technique may be employed to improve the program's computational efficiency, these efforts were considered beyond the scope of this study.

The programs flexibility to treat physical phenomena is demonstrated through solution to classical problems which consider:

I. Compressibility:

A. Incompressible (Blasius problem)

- B. Compressible (nozzle flow)
- II. Mach Regimes:
- A. Subsonic (M117 Warhead)
 - B. Transonic (M117 Warhead)
 - C. Supersonic (sharp-nosed projectile)
 - D. Hypersonic (re-entry vehicle)
- III. Boundary Layers:
- A. Laminar (Couette flow)
 - B. Turbulent (free jet)
- IV. Magnetic Reynolds Number regime:
- A. High magnetic Reynolds number (MHD shock detachment)
 - B. Low magnetic Reynolds number (MHD generator)
 - 1. Current stream function
 - 2. Electric potential
- V. Heat transfer
- A. Thermal conduction (transient temperature diffusion)
 - B. Viscous dissipation (boundary layer problem)
 - C. Joule heating (MHD generator)
 - D. Aerodynamic heating (ablated RV)
- VI. Shocks
- A. Normal shock (shock tube)
 - B. Oblique shock (sharp-nosed projectile)
 - C. Mach stem (regular-irregular Mach reflection)
 - D. Imbedded shock (ablated RV)
- VII. Time dependency

A. Transient (see problems above)

B. Steady state (see problems above)

The program employs three finite difference techniques to integrate time dependent variables:

- (A) gas dynamic integration is achieved using the Explicit Method developed by Matuska.
- (B) the solution of the elliptic equation (low Re_m) for the electric potential or stream current function employs the method of Successive Over-Relaxation (SOR).
- (C) the magnetic induction equation (high Re_m) and the Fourier thermal diffusion term in the energy equation are solved by either a central difference explicit scheme or an Alternating Direction Implicit (ADI) procedure.

An alternating direction implicit technique had been applied to the hydrodynamic equations, but its primary advantage of rapid convergence to steady state solution for some problems was overshadowed by its limitations (Section (1.3)) in treating transient cases and thus precluded its use in solving the conservation equations.

The overriding objective in developing this technique is to treat all interacting phenomena described by their governing equations simultaneously through a set of flexible, self-contained, autonomous finite difference equations where the only input consists of initial and boundary conditions and material constitutive relations.

The added difficulties in solving an MHD problem occur because of the "coupling" effect of the gas dynamic and electromagnetic fields which are interdependent. The MHD generator problem serves as a critical

Challenge for attaining this goal, and represents a clear test in establishing the program's capability to treat other equally difficult applications.

The difference method developed by Matuska and employed by the 2-D HULL Code is fully first order accurate. The HULL finite difference expressions approximate the conservation equations governing a compressible, non-conducting, inviscid fluid. This method was extended to include a two-dimensional single viscous fluid model with six fundamental equations governing the behavior of a conducting fluid: (1) continuity, (2) axial momentum, (3) radial momentum, (4) energy, and from Maxwell's equations and Ohm's Law, (5) magnetic induction or (6) the electric potential or current stream function.

CONSERVATION OF MASS:

$$\frac{d}{dt}(\rho) + \rho(\nabla \cdot \vec{v}) = 0 \quad (18)$$

CONSERVATION OF MOMENTUM:

$$\rho \frac{d}{dt}(\vec{v}) + \nabla p = -\rho \vec{g} - \nabla \cdot \vec{\tau} + \vec{j} \times \vec{B} \quad (19)$$

CONSERVATION OF ENERGY:

$$\rho \frac{d}{dt}(e) + \nabla \cdot (p\vec{v}) = -\rho \vec{v} \cdot \vec{g} - \nabla \cdot (\vec{\tau} \cdot \vec{v}) - \nabla \cdot \vec{q} \quad (20)$$

MAXWELL'S RELATIONS:

$$\nabla \times \vec{E} = -\frac{\delta}{\delta t}(\vec{B}) \quad (21)$$

$$\nabla \times \vec{B} = \mu_p \vec{j} \quad (22)$$

EQUATION OF STATE:

$$p = p(\rho, i) \quad (23)$$

CONSTITUTIVE RELATIONS:(A) STRESS TENSOR:(1) STOKES' LAW (LAMINAR):

$$\tau_{i,j} = \mu \left[\left(\frac{\partial u_i}{\partial X_j} + \frac{\partial u_j}{\partial X_i} \right) - \frac{2}{3} (\nabla \cdot \vec{v}) \delta_{i,j} \right] \quad (24)$$

where $u_1 = u$; $u_2 = v$; $X_1 = z$; $X_2 = r$

(2) TURBULENCE (EDDY MIXING LENGTH):

$$\tau = -(\mu + \mu_E) \frac{\delta}{\delta r} (u) \quad (25)$$

$$\mu_E = \lambda_E^2 \frac{\delta}{\delta r} (u) \quad (26)$$

(B) OHM'S LAW:

$$\vec{j} = \vec{\sigma} \cdot (\vec{E} + \vec{v} \times \vec{B}) \quad (27)$$

$$\vec{\sigma} = \frac{\sigma}{1 + \beta^2} \begin{bmatrix} 1 - \beta & \\ & \beta & 1 \end{bmatrix} \quad (28)$$

(C) FOURIER'S HEAT CONDUCTION LAW:

$$\vec{q} = -(\lambda + \lambda_t) \nabla T \quad (29)$$

BOUNDARY CONDITIONS:(A) SOLID BOUNDARY:

$$\vec{v} \cdot \vec{n} = 0 \quad (30)$$

(B) ELECTRODE:

$$\vec{E} \times \vec{n} = 0 \quad (31)$$

(C) INSULATOR:

$$\vec{j} \cdot \vec{n} = 0 \quad (32)$$

(D) electrical relation between the external and internal circuits of an MHD generator.

In order to minimize core requirements and computational cp (central processor) time of an already demanding computational method, three-dimensional problems were considered impractical. The model, however, can be easily extended to a third dimension when the development of advanced computers can accommodate the requirements of hydrocodes, in particular, the excessive cp* time. Turbulence was treated through a simple eddy viscosity model and no attempt was made to use sophisticated viscous theory, as this was also considered to be beyond the scope of this effort.

*cp - Central Processor

II. DISCUSSION OF TWO-DIMENSIONAL PLANE AND AXISYMMETRIC FINITE DIFFERENCE TECHNIQUE.

In Section 1.4, the equations describing the motion of a conducting fluid were presented. This section discusses a numerical procedure which "approximates" these equations by the method of finite differencing. In order to successfully develop a set of finite difference equations to a system of partial differential equations, three conditions must be satisfied: stability, convergence and compatibility. The objective of this study is to establish through a series of physical applications that the equations presented in this section do indeed satisfy these numerical conditions. The non-magnetic partial differential equations to be solved are:

- (1) Continuity
- (2) Axial momentum
- (3) Radial momentum
- (4) Energy

with four unknowns: p , u , v and e .

When including MHD effects, one needs in addition for large magnetic Reynolds number:

- (5) The magnetic induction equation

with the magnetic induction intensity as the additional unknown.

For problems of low magnetic Reynolds number, one needs

- (6) The elliptic partial differential equation governing the

electric potential or stream current function (ϕ or Ψ).

The additional unknown becomes ϕ or Ψ . Pressure, stress, currents and electric fields are computed from the variables discussed above with **the** additional relations: Equation of State, Ohm's Law and the constitutive relations correlating stress and strain.

2.1 Coordinate Systems

The initial development of a numerical scheme to solve the non-MHD gasdynamic equations treated axisymmetric problems with coordinates r (radial) and z (axial) with aximuthal terms constant ($d/d\theta = 0$). As $r \rightarrow \infty$, these equations reduced to a 2-D Cartesian system where the traditional x, y -axis coincide with the z, r coordinates, respectively.

When high Re_m MHD effects were treated, the magnetic induction was considered in the r, z, θ direction without violating the primary assumption of symmetry about the z -axis, since ($d/d\theta = 0$) terms were neglected and $\bar{j} \times \bar{B}$ and $\bar{j} \cdot \bar{E}$ contributions occur only in the r - z plane. In the case of low Re_m effects, problems were treated only in Cartesian coordinates and thus the electric potential, stream current function, currents, electric fields and consequently the Lorentz force and electrical energy terms $\bar{j} \times \bar{B}$ and $\bar{j} \cdot \bar{E}$ were expressed only in Cartesian coordinates.

In summary, all problems with the exception of the low Re_m MHD applications are solved in either 2-D axisymmetric or 2-D Cartesian coordinates. For low Re_m MHD problems, only 2-D Cartesian coordinates may be employed. In either case, r and z coordinate labels are employed.

2.2 Generalized Equations

The conservation equations are solved in two dimensions in either axisymmetric cylindrical coordinates or Cartesian coordinates as shown in Figure (2).

Equation (33) represents the conservation of mass:

$$\frac{\delta}{\delta t}(\rho) + \frac{1}{r^\alpha} \frac{\delta}{\delta r}(\rho \cdot v \cdot r^\alpha) + \frac{\delta}{\delta z}(\rho \cdot u) = 0 \quad (33)$$

where $\alpha = 0$ for rectangular coordinates and $\alpha = 1$ for cylindrical coordinates.

The conservation of axial and radial momentum*are described by

$$\frac{\delta}{\delta t}(u) + v \frac{\delta}{\delta r}(u) + u \frac{\delta}{\delta z}(u) = -\frac{1}{\rho} \frac{\delta}{\delta z}(p) - g_z - \frac{1}{\rho} \left[\frac{1}{r^\alpha} \frac{\delta}{\delta r}(r^\alpha \cdot \tau_{rz}) + \frac{\delta}{\delta z}(\tau_{zz}) \right] + \frac{1}{\rho} \{ [\vec{j} \times \vec{B}]_r \} \quad (34)$$

$$\frac{\delta}{\delta t}(v) + v \frac{\delta}{\delta r}(v) + u \frac{\delta}{\delta z}(v) = -\frac{1}{\rho} \frac{\delta}{\delta r}(p) - g_r - \frac{1}{\rho} \left[\frac{1}{r^\alpha} \frac{\delta}{\delta r}(r^\alpha \cdot \tau_{rr}) - \frac{\tau_{\theta\theta}}{r} + \frac{\delta}{\delta z}(\tau_{zz}) \right] + \frac{1}{\rho} \{ [\vec{j} \times \vec{B}]_r \} \quad (35)$$

The conservation of total energy is expressed as

$$\begin{aligned} \frac{\delta}{\delta t}(e) + v \frac{\delta}{\delta r}(e) + u \frac{\delta}{\delta z}(e) = & + \frac{1}{\rho} \left[\frac{1}{r^\alpha} \frac{\delta}{\delta r}(p \cdot v \cdot r^\alpha) + \frac{\delta}{\delta z}(p \cdot u) \right] \\ & - \frac{1}{\rho} \left[\frac{1}{r^\alpha} \frac{\delta}{\delta r}(\tau_{rr} \cdot v \cdot r^\alpha) + \frac{1}{r^\alpha} \frac{\delta}{\delta r}(\tau_{rz} \cdot r^\alpha \cdot u) + \frac{\delta}{\delta z}(v \cdot \tau_{rz}) + \frac{\delta}{\delta z}(u \cdot \tau_{zz}) \right] + \frac{1}{\rho} \{ [\vec{j} \cdot \vec{E}] \} \\ & - v \cdot g_r - u \cdot g_z - \frac{1}{\rho} \left[\frac{1}{r^\alpha} \frac{\delta}{\delta r}(-\lambda \cdot r^\alpha \cdot \frac{\delta}{\delta r}(T)) + \frac{\delta}{\delta z}(-\lambda \cdot \frac{\delta}{\delta z}(T)) \right] \end{aligned} \quad (36)$$

*Momentum is not conserved because of viscous dissipation and Joule heating. The expression "conservation of momentum" applies to the momentum balance including irreversible forces and the expression is not meant to be interpreted literally.

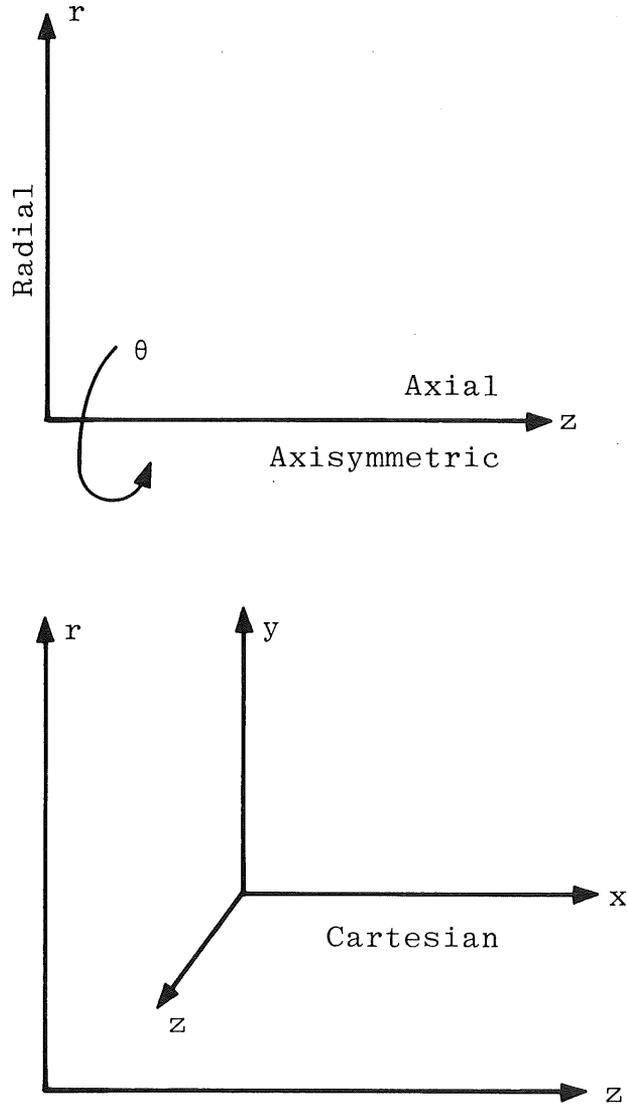


Fig. 2 Coordinate Systems

The electromagnetic influence of the Lorentz force in driving the fluid is represented explicitly as $\bar{j} \times \bar{B}$ in the momentum equation and $\bar{j} \cdot \bar{E}$ in the energy equation, where \bar{j} , \bar{B} and \bar{E} represent the current, magnetic induction and electric field vectors respectively. Equations (34) through (36) contain momentum and energy convection, pressure, gravitational, viscous and electromagnetic forces and the reversible and irreversible work performed by these same forces.

Total energy per unit mass is composed of internal and kinetic energy (assuming $p = \rho RT$):

$$e = \frac{1}{\gamma-1} \cdot \left(\frac{p}{\rho} \right) + \left(\frac{u^2 + v^2}{2} \right) \quad (37)$$

$$i = \frac{1}{\gamma-1} \cdot \left(\frac{p}{\rho} \right) \quad (38)$$

Equations (33) through (38) represent a set of coupled nonlinear partial differential equations which govern the behavior of a conducting, viscous perfect gas. Incorporating Stoke's Law, (stress proportional to the rate of strain) for laminar flow, in the form of constitutive relations (39) through (42), the system of equations becomes what is commonly referred to as the Navier-Stokes equations.

$$\tau_{rr} = - \left[2 \cdot \mu \frac{\delta}{\delta r} (v) - \frac{2}{3} \cdot \mu \left\{ \frac{1}{r^\alpha} \frac{\delta}{\delta r} (r^\alpha \cdot v) + \frac{\delta}{\delta z} (u) \right\} \right] \quad (39)$$

$$\tau_{zz} = - \left[2 \cdot \mu \frac{\delta}{\delta z} (u) - \frac{2}{3} \cdot \mu \left\{ \frac{1}{r^\alpha} \frac{\delta}{\delta r} (r^\alpha \cdot v) + \frac{\delta}{\delta z} (u) \right\} \right] \quad (40)$$

$$\tau_{\theta\theta} = - \left[2 \cdot \mu \frac{v}{r} - \frac{2}{3} \cdot \mu \left\{ \frac{1}{r^\alpha} \frac{\delta}{\delta r} (r^\alpha \cdot v) + \frac{\delta}{\delta z} (u) \right\} \right] \quad (41)$$

$$\tau_{rz} = - \mu \left[\frac{\delta}{\delta r} (u) + \frac{\delta}{\delta z} (v) \right] \quad (42)$$

or for turbulent flow:

$$\tau_{rz} = -(\mu + \mu_E) \left[\frac{\delta}{\delta r}(u) + \frac{\delta}{\delta z}(v) \right] \quad (43)$$

2.3 Problems of High Magnetic Reynolds Number

When considering problems of high magnetic Reynolds number and significant, induced magnetic induction, the Lorentz force ($\vec{j} \times \vec{B}$) may be replaced with the aid of Maxwell's equations as follows:

$$\vec{j} \times \vec{B} = \frac{1}{\mu} (\nabla \cdot \vec{B}) \cdot \vec{B} \quad (44)$$

Incorporating this term implicitly in the form of a magneto-stress tensor, the magneto-stress elements become:

$$\tau_{rr} = \left\{ \frac{B_r^2}{\mu_p} \right\} \quad (45)$$

$$\tau_{zz} = \left\{ \frac{B_z^2}{\mu_p} \right\} \quad (46)$$

$$\tau_{\theta\theta} = \left\{ \frac{B_\theta^2}{\mu_p} \right\} \quad (47)$$

$$\tau_{rz} = \left\{ \frac{B_r \cdot B_z}{\mu_p} \right\} \quad (48)$$

which are added to the viscous stress elements.

The magnetic induction equation has three components yielding the induced fields in the azimuthal, radial and axial directions, respectively (with zero Hall current):

$$\frac{\delta}{\delta t}(B_\theta) - \frac{\delta}{\delta z}(B_\theta \cdot u) - \frac{\delta}{\delta r}(B_\theta \cdot v) = \frac{\delta}{\delta r} \left[\frac{1}{\sigma} \frac{1}{r^\alpha} \frac{\delta}{\delta r} (r^\alpha \cdot B_\theta) \right] + \frac{\delta}{\delta z} \left[\frac{1}{\sigma} \frac{\delta}{\delta z} \left(\frac{B_\theta}{\mu_p} \right) \right] \quad (49)$$

$$\frac{\delta}{\delta t}(B_r) - \frac{\delta}{\delta z}(B_r \cdot u) + \frac{\delta}{\delta z}(B_z \cdot v) = + \frac{\delta}{\delta r} \left[\left(-\frac{1}{\sigma} \frac{1}{r^\alpha} \frac{\delta}{\delta r} \left(\frac{r^\alpha \cdot B_r}{\mu_p} \right) \right) \right] + \frac{\delta}{\delta z} \left[\left(-\frac{1}{\sigma} \frac{\delta}{\delta z} \left(\frac{B_r}{\mu_p} \right) \right) \right] \quad (50)$$

$$\begin{aligned} \frac{\delta}{\delta t}(B_z) + \frac{1}{r^\alpha} \frac{\delta}{\delta r}(r^\alpha \cdot u \cdot B_r) - \frac{1}{r^\alpha} \frac{\delta}{\delta r}(r^\alpha \cdot v \cdot B_z) &= \frac{\delta}{\delta r} \left[\left(-\frac{1}{\sigma} \frac{1}{r^\alpha} \frac{\delta}{\delta r} \left(\frac{r^\alpha \cdot B_z}{\mu_p} \right) \right) \right] \\ &+ \frac{\delta}{\delta z} \left[\left(-\frac{1}{\sigma} \frac{\delta}{\delta z} \left(\frac{B_z}{\mu_p} \right) \right) \right] \end{aligned} \quad (51)$$

Since this program is two-dimensional, all derivatives in the azimuthal direction have been neglected.

In equation (52), the hydrostatic and magnetic pressure were added to give the true pressure of the medium.

$$p = p + \left\{ \left(\frac{B_r^2}{2\mu_p} + \frac{B_z^2}{2\mu_p} + \frac{B_\theta^2}{2\mu_p} \right) \right\} \quad (52)$$

If $\vec{j} \times \vec{B}$ and $\vec{j} \cdot \vec{E}$ appear in the momentum and energy equations, then the stress tensor and pressure term do not contain the magnetic components and equations (49) through (51) need not be solved. If the magneto-stress terms are employed, then $\vec{j} \times \vec{B}$ and $\vec{j} \cdot \vec{E}$ do not appear explicitly in the momentum and energy equations and currents and electric fields are not (necessarily) computed.

2.4 Problems of Low Magnetic Reynolds Number

Calculation of the electric fields and currents is developed from the solution of the elliptic partial differential equation (PDE):

$$\frac{\delta}{\delta z} \left(\frac{\delta}{\delta z} (F) \right) + \frac{\delta}{\delta r} \left(\frac{\delta}{\delta r} (F) \right) + A \frac{\delta}{\delta z} (F) + B \frac{\delta}{\delta r} (F) + C = 0 \quad (53)$$

where F represents either the electric potential or the current stream function (ϕ or Ψ), and coefficients A , B and C are functions of u , v , σ , β and \bar{B} . Equation (53) was derived from Maxwell's relations.

$$\nabla \times \vec{E} = -\frac{\delta}{\delta t}(B) \approx 0 \quad (54)$$

and neglecting the rate of change of charge density

$$\nabla \cdot \vec{j} = 0 \quad (55)$$

The derivation of this PDE and its coefficients follows.

A scalar potential is defined such that its gradient yields components of the electric field:

$$\vec{E} = -\nabla\phi \quad (56)$$

consistent with equation (57)

$$-\nabla \times \nabla\phi = 0 \quad (57)$$

Employing Ohm's Law, the current is found to be

$$\vec{j} = \sigma(\vec{E} + \vec{v} \times \vec{B}) - \frac{\beta}{|\vec{B}|}(\vec{j} \times \vec{B}) \quad (58)$$

where the first term represents the sum of the applied and induced currents resulting from the electric field and the second term is the Hall current.

Expressing Ohm's Law through a tensor conductivity:

$$\vec{j} = \bar{\bar{\sigma}} \cdot \vec{E} \quad (59)$$

the components of current take the form:

$$j_z = \frac{\sigma}{1+\beta^2} [(E_z + vB) - \beta(E_r - uB)] \quad (60)$$

$$j_r = \frac{\sigma}{1+\beta^2} [\beta(E_z + vB) + (E_r - uB)] \quad (61)$$

where

j_r, j_z = r and z components of current

u, v = r and z components of particle velocity

E_r, E_z = r and z components of electric field

σ = scalar conductivity

β = Hall parameter

B = θ component of the magnetic induction*

and from Equation (56)

$$E_z = -\frac{\delta}{\delta z}(\phi) \quad E_r = -\frac{\delta}{\delta r}(\phi) \quad (62)$$

Substituting Equations (60), (61), and (62) into Equation (55),

Equation (63) results:

$$\begin{aligned} & \frac{\delta}{\delta z} \left(\frac{\delta}{\delta z}(\phi) \right) + \frac{\delta}{\delta r} \left(\frac{\delta}{\delta r}(\phi) \right) + \left[\frac{1}{\sigma_+} \frac{\delta}{\delta z}(\sigma_+) + \beta \frac{1}{\sigma_+} \frac{\delta}{\delta r}(\sigma_+) + \frac{\delta}{\delta r}(\beta) \right] \frac{\delta}{\delta z}(\phi) \\ & + \left[\frac{1}{\sigma_+} \frac{\delta}{\delta r}(\sigma_+) - \beta \frac{1}{\sigma_+} \frac{\delta}{\delta z}(\sigma_+) - \frac{\delta}{\delta z}(\beta) \right] \frac{\delta}{\delta r}(\phi) + [vB + \beta uB] \frac{1}{\sigma_+} \frac{\delta}{\delta z}(\sigma_+) \\ & - \frac{\delta}{\delta z}(vB + \beta uB) - [uB - \beta vB] \frac{1}{\sigma_+} \frac{\delta}{\delta r}(\sigma_+) + \frac{\delta}{\delta r}(uB - \beta vB) = 0 \end{aligned} \quad (63)$$

where

$$\sigma_+ = \frac{\sigma}{1+\beta^2} \quad (64)$$

*r and z magnetic fields are not treated since the MHD generator modeled in Section (4) does not require it.

From Equation (55), one may define a current stream function Ψ as

$$j_z = \frac{\delta}{\delta r}(\Psi) \quad j_r = -\frac{\delta}{\delta z}(\Psi) \quad (65)$$

Employing Equations (54) and (58), Equation (66) is developed:

$$\begin{aligned} & \frac{\delta}{\delta z} \left(\frac{\delta}{\delta z}(\Psi) \right) + \frac{\delta}{\delta r} \left(\frac{\delta}{\delta r}(\Psi) \right) + \left[-\frac{1}{\sigma_+} \frac{\delta}{\delta z}(\sigma_+) + \beta \frac{1}{\sigma_+} \frac{\delta}{\delta r}(\sigma_+) + \frac{\delta}{\delta r}(\beta) \right] \frac{\delta}{\delta z}(\Psi) + \\ & \left[-\frac{1}{\sigma_+} \frac{\delta}{\delta r} \left(\frac{\delta}{\delta r} \right) - \beta \frac{1}{\sigma_+} \frac{\delta}{\delta z}(\sigma_+) + \frac{\delta}{\delta z}(\beta) \right] \frac{\delta}{\delta r}(\Psi) + \sigma \left[\left(\frac{\delta}{\delta z}(\text{Bu}) + \frac{\delta}{\delta r}(\text{Bv}) \right) \right] = 0 \quad (66) \end{aligned}$$

2.5 HULL Finite Difference Equations

A method developed by Daniel Matuska for computing hydrodynamic properties of a fluid was employed. A discussion of the HULL finite difference technique appears in Appendix (A); the salient features are outlined below:

Calculations are performed in two phases: phase I, integrating the "Lagrangian terms" (coordinate system fixed to the fluid element) and phase II treating the convective terms by transporting mass.

A grid is initially generated as shown in Figure (3). Parallel, although not necessarily equally spaced lines are constructed in both the r and z directions. These grid lines form a mesh with elements or cells defined by the four grid lines bordering it. Each cell is assigned an index value in much the same manner that elements of a matrix are assigned identification. The lower left-hand boundary cell has indices of $i=1$, $j=1$ and incrementing values of i as one marches in the vertical (r) direction or incrementing values of j as one marches in the axial (z) direction. There are certain hydrodynamic (thermodynamic) variables assigned to each cell initially, with updated values of these variables stored in the ensuing calculations. These variables are density, axial velocity, radial velocity and total energy (magnetic and electric fields are added later). Other properties, such as pressure or internal energy, can be computed directly from these parameters. In phase I calculations, values of ρ , u , v and e at the boundary of the cell are needed; therefore, indices: $i, j-\frac{1}{2}$; $i-\frac{1}{2}, j$; $i, j+\frac{1}{2}$; and $i+\frac{1}{2}, j$ refer to such values (see Figure (4)).

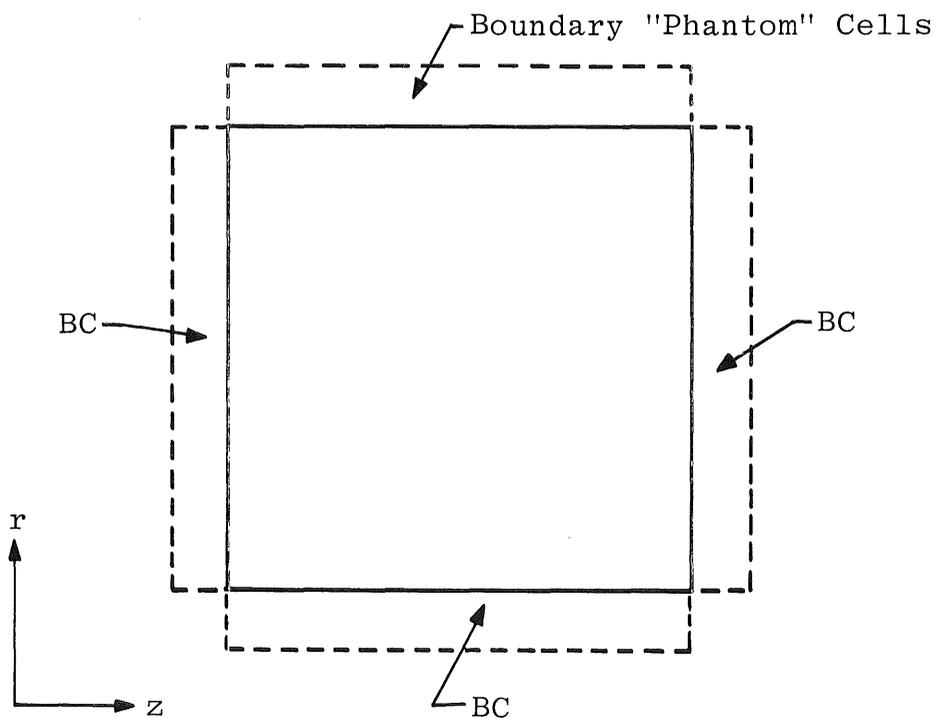
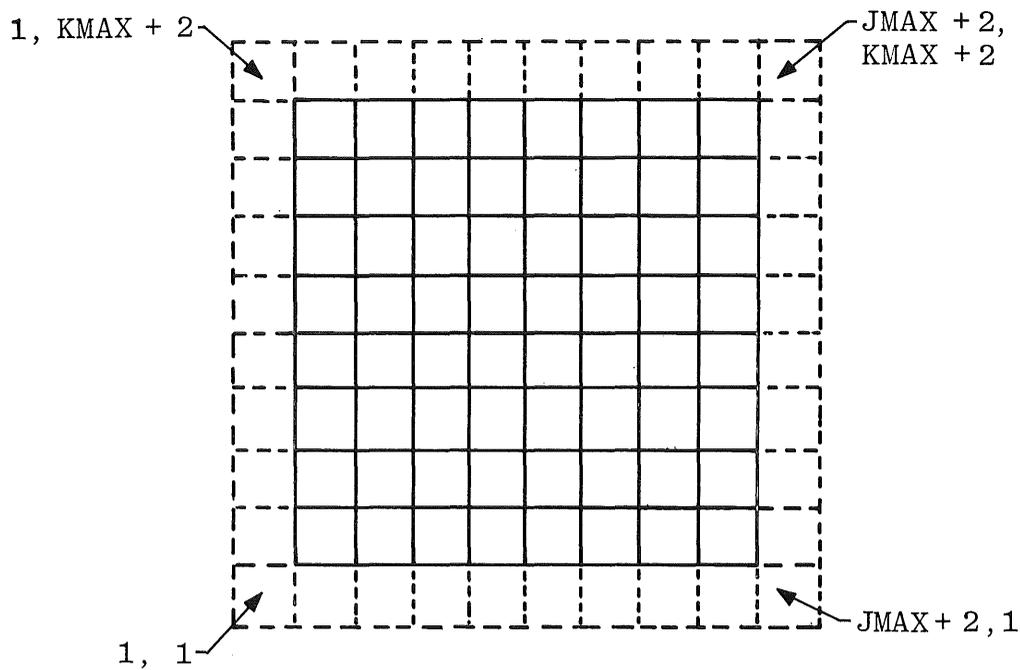


Fig. 3 Grid Setup

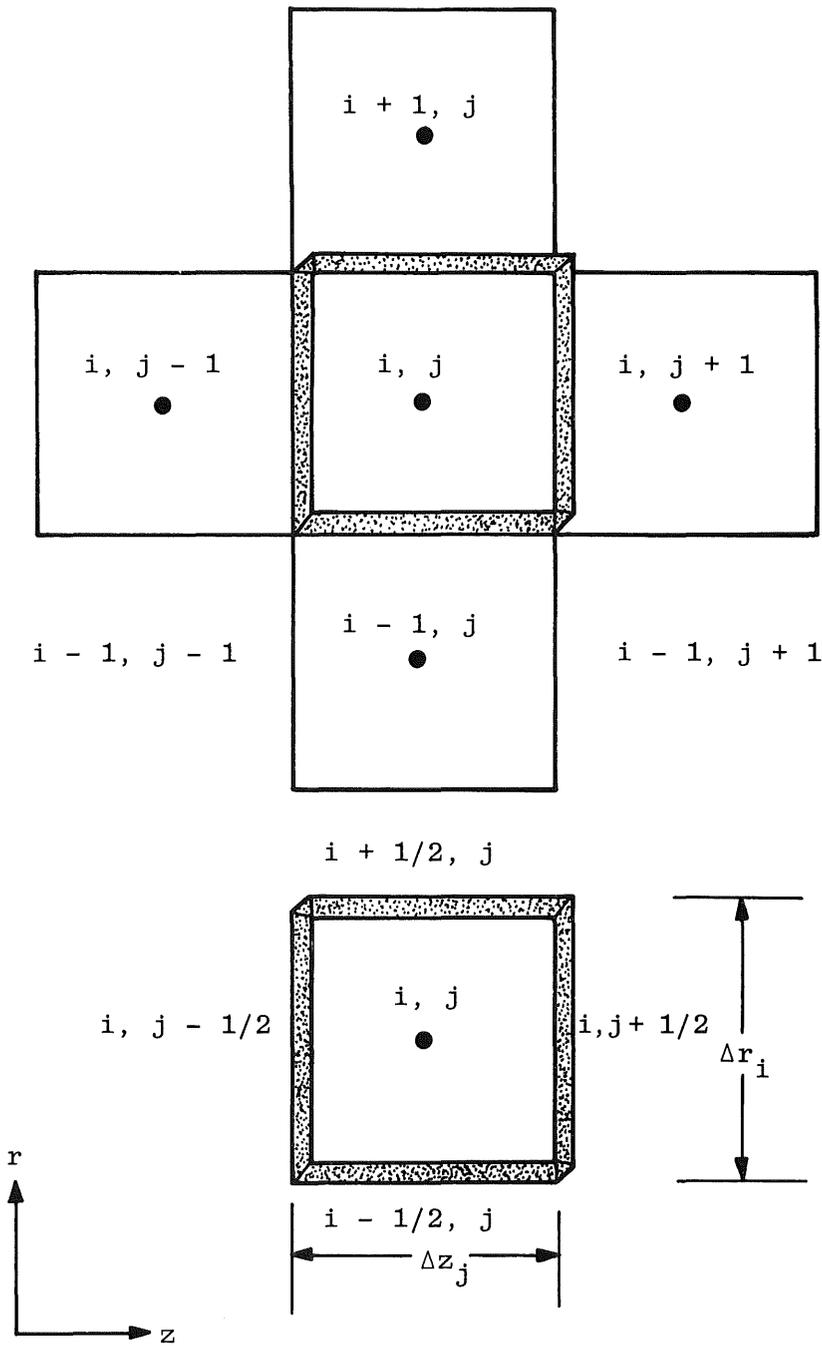


Fig. 4 Subscript Notation for Cell Identification

Matuska solved Equations (18) through (20) and (23), excluding the viscous, magnetic and heat conduction terms, whereas the development of a numerical solution to equations (18) through (29) in their entirety makes up the subject of this study.

Employing those numerical features characterizing HULL which distinguish its methodology from other finite-difference techniques, calculations are:

- (I) time and space centered, analogous to a "predictor-corrector" integration.
- (II) performed in two phases; phase I: calculating the change in momentum and energy in a Lagrangian reference frame (no convection) (Figure (5)) and phase II: employing the "donor-receiver" technique where mass, momentum and energy are transported (convected) between neighboring cells.

Figure (6) illustrates a cell with indices assigned at the cell center and four cell interfaces. The values of ρ , u , v and e (or p) are known at $t(n)$. The procedure for determining ρ , u , v , and e at $t(n+1)$ is as follows:

Referring to Figure (6), ρ , u , v and p

- (1) are defined at each interface based on cell center values at $t(n)$, Figure (6a).
- (2) are updated to $t(n+\frac{1}{2})$ by "predicting" values based on the conservation equations - time centering (Figure (6b)).
- (3) at cell centers are computed by again integrating using the interface values - space centering.

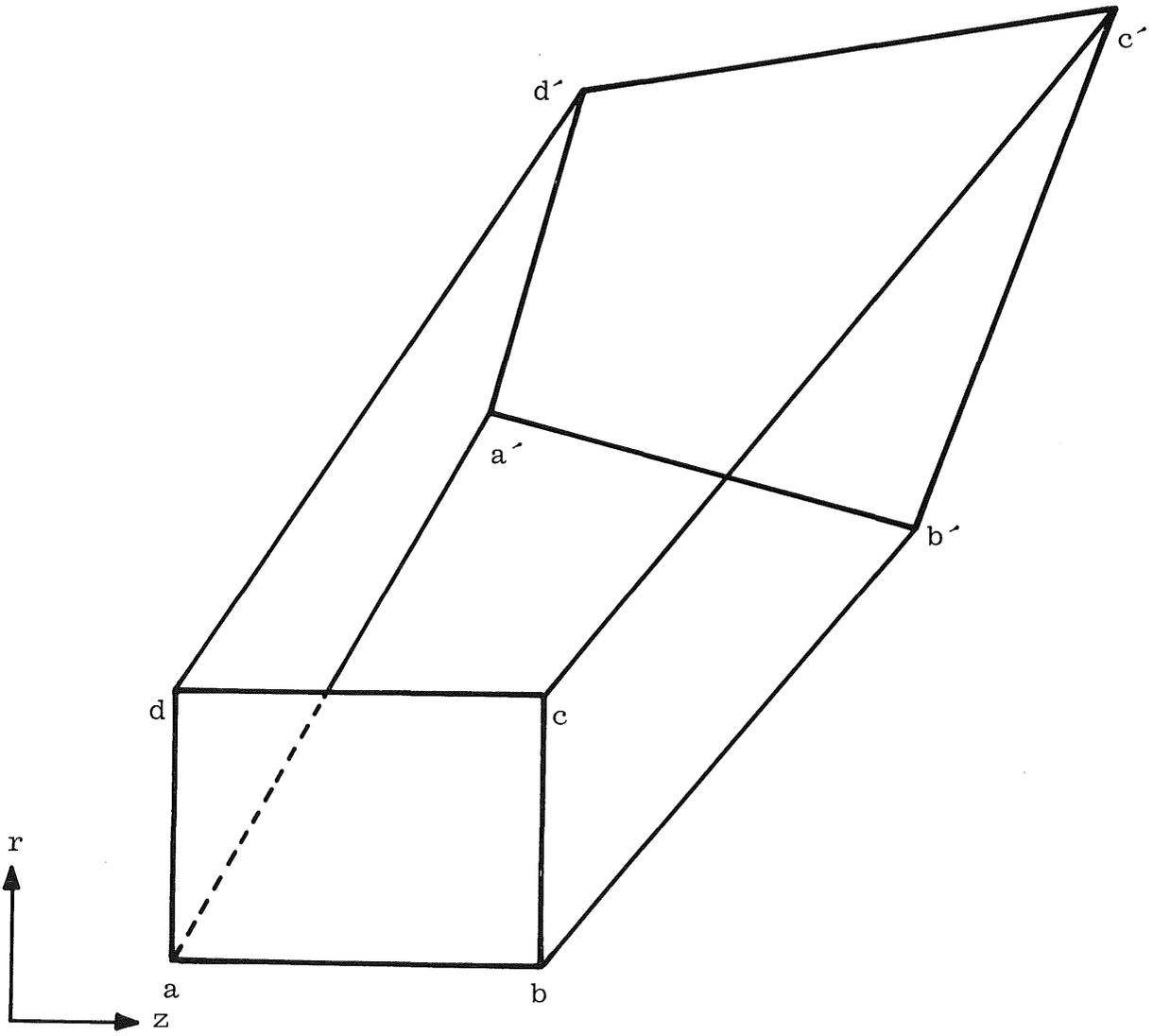


Fig. 5 Lagrangian Integration

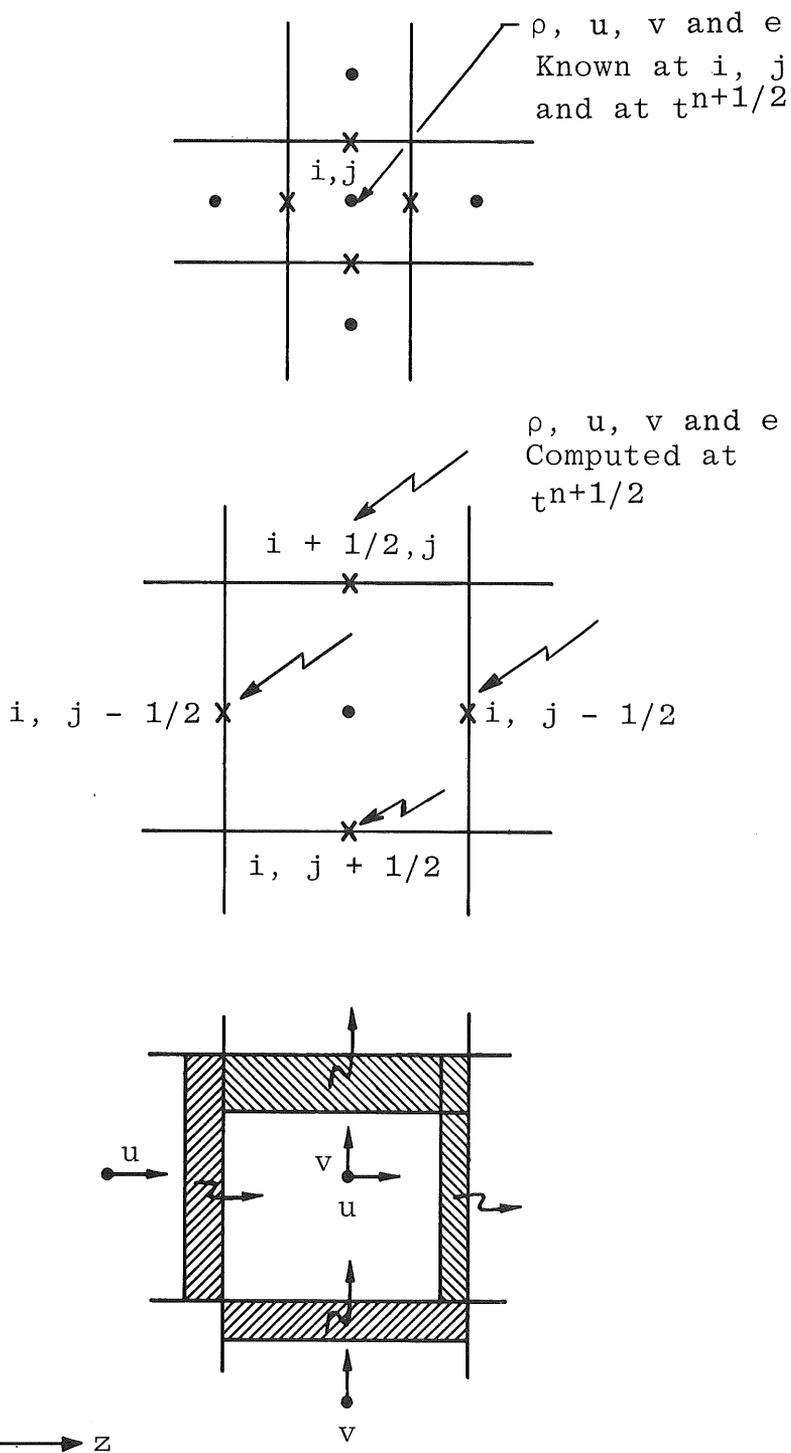


Fig. 6 Integration Technique of HULL

(4) at $t(n+1)$ are employed to flux mass from cell to cell and thus restore the distorted Lagrangian mesh (Figure (6c)) to its original position.

The fundamental purpose of time and space centering is to preserve numerical stability, especially in regions of small hydrodynamic gradients. Further, by employing the donor-receiver technique in phase II and "re-zoning" the displaced Lagrangian mesh back to its original position, the calculation remains Eulerian in nature.

2.6 Curved Boundaries

Conditions for a solid boundary are represented by Equations (30) to (32). If the body is curved, as is shown in Figure (7), the angle of curvature is determined over segments of the curve and the unit normal vector is evaluated over the segment chord. Thus, cells lying on the solid boundary are "oriented" so that the bodies true streamline is reflected in the calculation.

2.7 Finite Difference Equations (FDEs)

An introductory explanation of the HULL FDEs appear in Appendix (A). This section examines the complete set of equations, including viscous, thermal, magnetic and electric terms all in finite difference form.

Phase I (Lagrangian Frame of Reference)

Referring to Figure (4) where the indices i, j are defined, calculations made in a Lagrangian frame of reference consists of traveling with the moving fluid or mass particles or in the case of this program, traveling with cells (or grids) of fixed mass. In Equation (69) the cell mass is computed by taking a circular cut of the cell from $(r(i+\frac{1}{2}), r(i-\frac{1}{2}))$ to

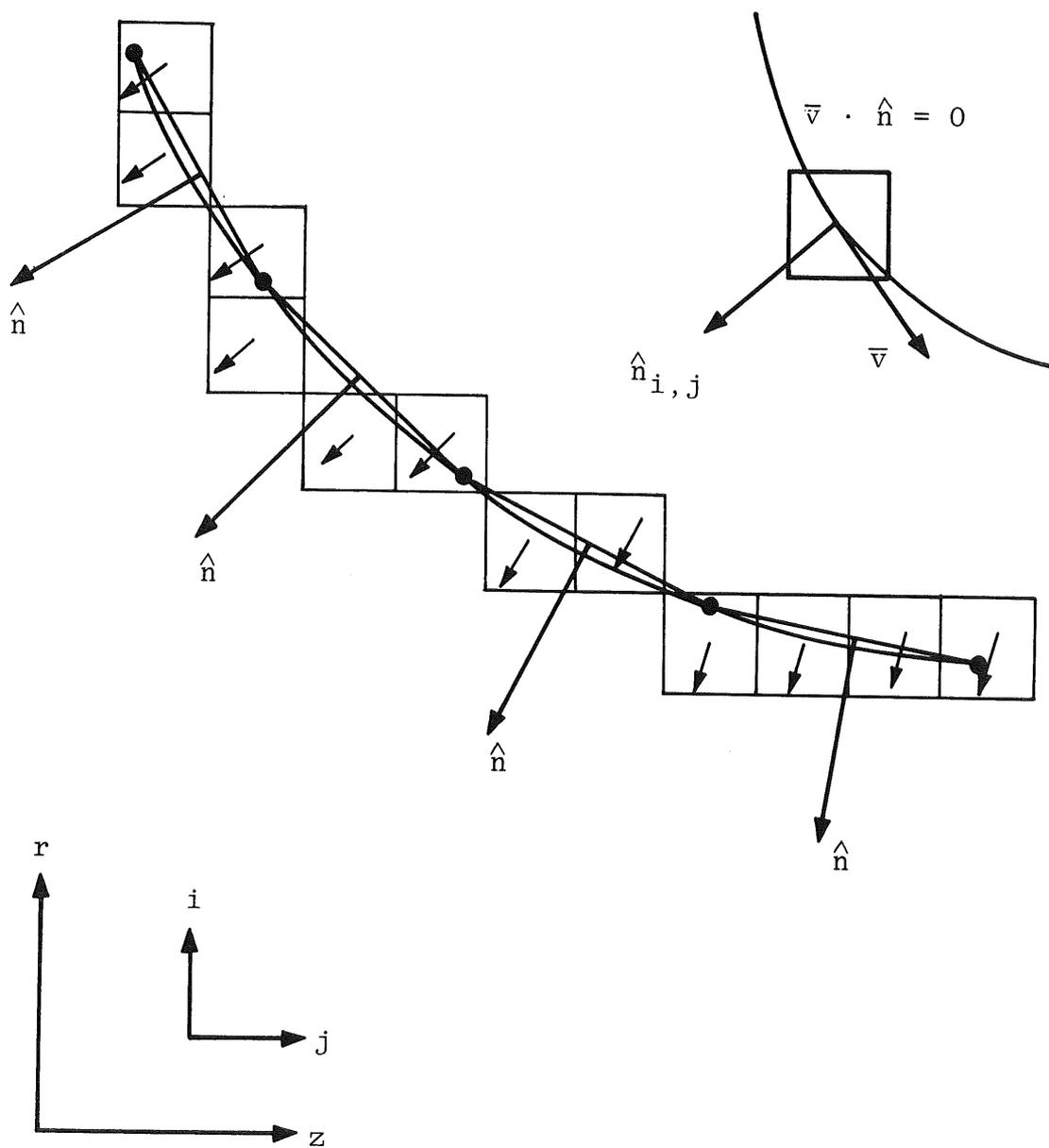


Fig. 7 Oblique or Curvilinear Boundary Conditions

the origin (see Figure (8)). In Cartesian coordinates, the volume sweep consumes the cell area x unit depth.

$$r_{i-1/2} = r_i - \frac{\Delta r_i}{2} \quad (67)$$

$$r_{i+1/2} = r_i + \frac{\Delta r_i}{2} \quad (68)$$

$$M_{i,j}^n = \rho_{i,j}^n \cdot \pi \cdot (r_{i+1/2}^2 - r_{i-1/2}^2) \Delta z_j \quad (69)$$

Equations (70) and (71) reveal the average densities at the cell interface

$$\rho_{i+1/2,j}^n = \frac{(M_{i,j}^n + M_{i+1,j}^n)}{\pi(r_{i+3/2}^2 - r_{i-1/2}^2) \Delta z_j} \quad (70)$$

$$\rho_{i,j+1/2}^n = \frac{(M_{i,j}^n + M_{i,j+1}^n)}{\pi(r_{i+1/2}^2 - r_{i-1/2}^2) (\Delta z_j + \Delta z_{j+1})} \quad (71)$$

at time (n). In order to maintain stability and convergence in all calculations, integrations must be spatially and temporally centered. Thus in the fashion of a predictor-corrector integration, values are computed at time $(n+1/2)$ and at $i+1/2, j+1/2, i-1/2, j-1/2$ and these values used in the integration to compute fluid properties at the center of each cell and at time $(n+1)$. Equations (72) and (73) generate cell interface values of density at time $(n+1/2)$.

$$\rho_{i+1/2,j}^{n+1/2} = \rho_{i+1/2,j}^n \left\{ 1 - \frac{\Delta t^{n+1/2} (r_{i+1} \cdot v_{i+1,j}^n - r_i \cdot v_{i,j}^n)}{2r_{i+1/2} (r_{i+1} - r_i)} \right\} \quad (72)$$

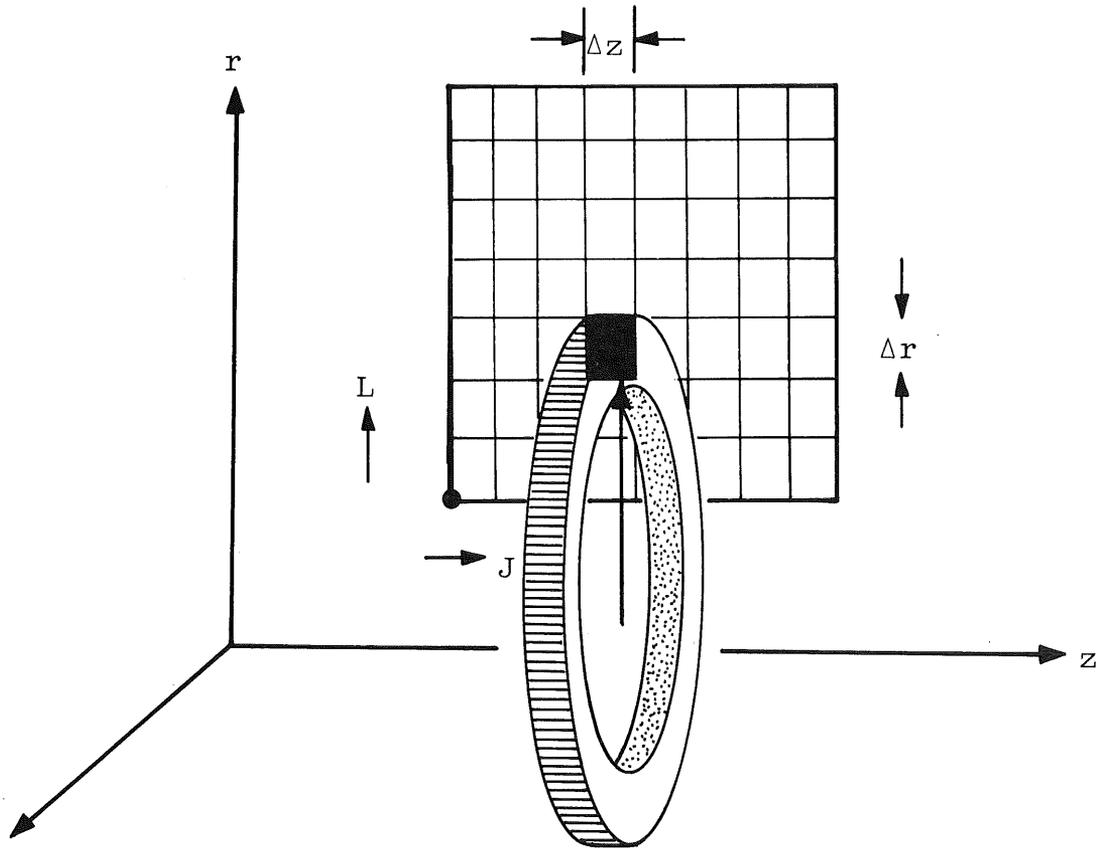


Fig. 8 Volume Element of a Cell

$$\rho_{i,j+\frac{1}{2}}^{n+\frac{1}{2}} = \rho_{i,j+\frac{1}{2}}^n \left\{ 1 - \frac{\Delta t^{n+\frac{1}{2}} (u_{i,j+1}^n - u_{i,j}^n)}{2(z_{j+1} - z_j)} \right\} \quad (73)$$

In Cartesian coordinates the mass and density is given by:

$$M_{i,j}^n = \rho_{i,j}^n \Delta r_i \Delta z_j \quad (74)$$

and

$$\rho_{i+\frac{1}{2},j}^n = \frac{(M_{i,j}^n + M_{i+1,j}^n)}{\Delta r_i \Delta z_j} \quad (75)$$

However, as r goes to infinity, ρ (cylindrical) approaches ρ (Cartesian) and therefore Equations (69) through (73) are sufficient for both coordinate systems.

A time dependent equation for pressure, based on the conservation of mass, momentum and energy (Appendix (B)) includes contributions from pressure induced expansion (or compression), ohmic heating and viscous dissipation. All magnetic and electric terms, such as ohmic heating, may be represented either by a magnetic stress tensor employing the second-order elliptic magnetic induction equation, as derived from Maxwell's relations or by solution to a second-order elliptic stream current or potential equation as described on page 32. In the first case, currents are generated by the induced magnetic fields according to Equation (22) and thus are contained implicitly in the "divergence" of a magneto-stress tensor. In the second case, currents are explicitly defined through the use of potential or (current) stream functions and Ohm's Law. Either the induction equation or the stream function/potential equation may be employed as each equally represents the

influence of electric and magnetic effects on the flow field. (Later in this section a more detailed discussion of the calculation of currents and the electric field can be found.)

The fundamental purpose of time and space-centering all calculations in Phase I, as developed by Matuska, was to avoid instabilities resulting from forces creating small momentum gradients.[†] While p and $j \times \bar{B}$ forces create severe gradients, viscous forces tend to diffuse momentum and do not pose a significant threat to stability as compared with other MHD forces.* It is primarily for this reason that pressure and electromagnetic terms are time and space centered, whereas viscous terms are not. Thermal conduction is also neglected at this stage because of its relatively smaller contribution to the momentum and energy equations over a time step. Computing the pressure at the cell interface at time $(n+\frac{1}{2})$ (see Appendix (B)):

$$p_{i+\frac{1}{2},j}^{n+\frac{1}{2}} = p_{i+\frac{1}{2},j}^n \left\{ 1 + \frac{\Delta t^{n+\frac{1}{2}} \gamma (r_{i,l} \cdot v_{i+1,j}^n - r_i \cdot v_{i,j}^n)}{2r_{i+\frac{1}{2}}(r_{i+1} - r_i)} \right\} \\ + (\gamma - 1) (j_{r_{i+\frac{1}{2},j}^n} \cdot j_{r_{i+\frac{1}{2},j}^n} + j_{z_{i+\frac{1}{2},j}^n} \cdot j_{z_{i+\frac{1}{2},j}^n}) / \sigma_{i+\frac{1}{2},j}^n \quad (76)$$

$$p_{i,j+\frac{1}{2}}^{n+\frac{1}{2}} = p_{i,j+\frac{1}{2}}^n \left\{ 1 + \frac{\Delta t^{n+\frac{1}{2}} \gamma (u_{i,j+1}^n - u_{i,j}^n)}{2(z_{j+1} - z_j)} \right\} \\ + (\gamma - 1) (j_{r_{i,j+\frac{1}{2}}^n} \cdot j_{r_{i,j+\frac{1}{2}}^n} + j_{z_{i,j+\frac{1}{2}}^n} \cdot j_{z_{i,j+\frac{1}{2}}^n}) / \sigma_{i,j+\frac{1}{2}}^n \quad (77)$$

*provided the time step is bounded (Eqns (16) and (17))

[†]Instability developing from severe gradients is eliminated by fluxing (Phase II).

If the current stream function is employed, the space-centered currents and electric fields are defined at time (n) by:

$$j_{z,i,j}^n = + \frac{\delta}{\delta r} (\psi^n) = \frac{\psi_{i+1,j}^n - \psi_{i-1,j}^n}{2\Delta r_i} \quad (78)$$

$$j_{r,i,j}^n = - \frac{\delta}{\delta z} (\psi^n) = - \frac{\psi_{i,j+1}^n - \psi_{i,j-1}^n}{2\Delta z_j} \quad (79)$$

$$E_{z,i,j}^n = (j_{z,i,j}^n + \beta_{i,j}^n j_{r,i,j}^n) / \sigma_{i,j}^n - v_{i,j}^n B_{\theta,i,j}^n \quad (80)$$

$$E_{r,i,j}^n = (j_{r,i,j}^n - \beta_{i,j}^n j_{z,i,j}^n) / \sigma_{i,j}^n + u_{i,j}^n B_{\theta,i,j}^n \quad (81)$$

If the electric potential is used, the space-centered currents and electric fields become at time (n):

$$E_{z,i,j}^n = - \frac{\delta}{\delta z} (\phi^n) = - \frac{\phi_{i,j+1}^n - \phi_{i,j-1}^n}{2\Delta z_j} \quad (82)$$

$$E_{r,i,j}^n = - \frac{\delta}{\delta r} (\phi^n) = - \frac{\phi_{i+1,j}^n - \phi_{i-1,j}^n}{2\Delta r_i} \quad (83)$$

$$j_{z,i,j}^n = \sigma_{i,j}^n [(E_{z,i,j}^n + v_{i,j}^n B_{\theta,i,j}^n) - \beta_{i,j}^n (E_{r,i,j}^n - u_{i,j}^n B_{\theta,i,j}^n)] \quad (84)$$

$$j_{r,i,j}^n = \sigma_{i,j}^n [\beta_{i,j}^n (E_{r,i,j}^n + v_{i,j}^n B_{\theta,i,j}^n) + (E_{z,i,j}^n - u_{i,j}^n B_{\theta,i,j}^n)] \quad (85)$$

The choice of using either the stream function or potential is usually dictated by the electrical boundary conditions. If the voltage (or potential) at the electrodes is known, the potential is employed. If the external currents at the electrodes are known, then a stream function

is used. Further, since the potential is constant on a conductor and the stream function is constant on an insulator, defining infinity for a particular generator might strongly influence the choice of one method over the other.

The values of the currents at the cell interfaces are computed by using the values of ϕ and Ψ of the two cells adjoining at the interface and employing the velocities, conductivity, Hall parameter and magnetic fields evaluated at the interface. The relation between the stream function and potential at the cell center and time (n) becomes:

$$\Psi_{i,j}^n = \Psi_{i,j-1}^n - (j_{r_{i,j}}^n + j_{r_{i,j-\frac{1}{2}}}^n) / \{2 \cdot (z_j - z_{j-1})\} \quad (86)$$

$$\phi_{i,j}^n = \phi_{i,j-1}^n - (E_{r_{i,j}}^n + E_{r_{i,j-\frac{1}{2}}}^n) / \{2 \cdot (z_j - z_{j-1})\} \quad (87)$$

If the magnetic induction equation is employed ($Re_m \gg 1$), the magnetic stress elements become:

$$\tau_{rr}^n_{i+1,j} = \frac{B_{r_{i+1,j}}^n \cdot B_{r_{i+1,j}}^n}{\mu_p} \quad (88)$$

$$\tau_{zz}^n_{i,j+1} = \frac{B_{z_{i,j+1}}^n \cdot B_{z_{i,j+1}}^n}{\mu_p} \quad (89)$$

$$\tau_{\theta\theta}^n_{i+1,j} = \frac{B_{z_{i,j+1}}^n \cdot B_{z_{i,j+1}}^n}{\mu_p} \quad (90)$$

$$\tau_{rz}^n_{i+1,j+1} = \frac{2B_{r_{i+1,j+1}}^n + B_{r_{i+1,j}}^n + B_{r_{i,j+1}}^n}{4\mu_p} \cdot \frac{2B_{z_{i+1,j+1}}^n + B_{z_{i+1,j}}^n + B_{z_{i,j+1}}^n}{4\mu_p} \quad (91)$$

$$\tau_{rr}^n = \frac{B_{r,i,j}^n \cdot B_{r,i,j}^n}{\mu_p} \quad (92)$$

$$\tau_{zz}^n = \frac{B_{z,i,j}^n \cdot B_{z,i,j}^n}{\mu_p} \quad (93)$$

$$\tau_{\theta\theta}^n = \frac{B_{\theta,i,j}^n \cdot B_{\theta,i,j}^n}{\mu_p} \quad (94)$$

$$\tau_{rz}^n = \frac{B_{r,i,j}^n \cdot B_{z,i,j}^n}{\mu_p} \quad (95)$$

The Lagrangian velocities at the interface at time $(n+1/2)$ may now be computed:

$$u_{i,j+1/2}^{n+1/2} = u_{i,j+1/2}^n - \frac{\Delta t^{n+1/2}}{2\rho_{i,j+1/2}^{n+1/2}} \left(\frac{p_{i,j+1}^n - p_{i,j}^n}{z_{j+1} - z_j} \right) - g_z \frac{\Delta t^{n+1/2}}{2} - \frac{\Delta t^{n+1/2}}{2\rho_{i,j+1/2}^{n+1/2}} \left\{ \frac{\tau_{zz}^n}{\Delta z_{j+1}} - \tau_{zz,i,j+1}^n - \tau_{zz,i,j}^n \right. \\ \left. + \frac{r_{i+1} \tau_{rz,i+1,j+1}^{n+1/2} - r_i \tau_{rz,i,j}^n}{r_{i+1/2} \cdot \Delta r_{i+1}} \right\} + \frac{\Delta t^{n+1/2}}{2\rho_{i,j+1/2}^{n+1/2}} j r_{i,j+p} B_{\theta,i,1/2,j}^{n+1/2} \quad (96)$$

$$v_{i+1/2,j}^{n+1/2} = - \frac{\Delta t^{n+1/2}}{2\rho_{i+1/2,j}^{n+1/2}} \left(\frac{p_{i+1,j}^{n+1} - p_{i,j}^n}{r_{i+1} - r_i} \right) - g_r \frac{\Delta t^{n+1/2}}{2} - \frac{\Delta t^{n+1/2}}{2\rho_{i+1/2,j}^{n+1/2}} \left\{ \frac{\tau_{rz}^n}{\Delta z_{j+1}} - \tau_{rz,i+1,j+1}^n - \tau_{rz,i,j}^n \right. \\ \left. + \frac{r_{i+1} \tau_{rr,i+1,j}^n - r_i \tau_{rr,i,j}^n}{r_{i+1/2} \cdot \Delta r_{i+1}} - \frac{\tau_{\theta\theta}^{n+1/2}}{r_{i+1/2}} \right\} - \frac{\Delta t^{n+1/2}}{2\rho_{i+1/2,j}^{n+1/2}} j z_{i+1/2,j}^n B_{\theta,i+1/2,j}^{n+1/2} \quad (97)$$

Having predicted the values of pressure, density, velocity and currents at each cell interface at time $(n+1/2)$, the final stage of Phase I, computing u, v and e at time $(n+1)$ (excluding convection), proceeds.

The rate of strain at each cell interface is computed based on values of u and v at time (n) .

$$\epsilon_{r_{i+\frac{1}{2},j}}^n = \frac{v_{i+1,j}^n - v_{i,j}^n}{r_{i+1} - r_i} \quad (98)$$

$$\epsilon_{z_{i,j+\frac{1}{2}}}^n = \frac{u_{i,j+1}^n - u_{i,j}^n}{z_{j+1} - z_j} \quad (99)$$

$$\epsilon_{\theta_{i+\frac{1}{2},j}}^n = \frac{v_{i+1,j}^n + v_{i,j}^n}{2r_{i+\frac{1}{2}}} \quad (100)$$

$$\epsilon_{rz_{i+\frac{1}{2},j+\frac{1}{2}}}^n = \frac{u_{i+1,j}^n - u_{i,j}^n}{r_{i+1} - r_{i-\frac{1}{2}}} + \frac{v_{i,j+1}^n - v_{i,j}^n}{z_{j+1} - z_j} \quad (101)$$

$$\epsilon_{i+1,j+1}^n = \epsilon_{r_{i+\frac{1}{2},j}}^n + \epsilon_{z_{i,j+\frac{1}{2}}}^n + \epsilon_{\theta_{i+\frac{1}{2},j}}^n \quad (102)$$

Next, calculating the stress tensor elements at each cell interface at time (n) :

for laminar flow:

$$\tau_{rr_{i+\frac{1}{2},j}}^n = -2\mu_{i+\frac{1}{2},j}^n \epsilon_{r_{i+\frac{1}{2},j}}^n + \frac{2}{3}\mu_{i+\frac{1}{2},j}^n \epsilon_{i+1,j+1}^n \quad (103)$$

$$\tau_{zz_{i,j+\frac{1}{2}}}^n = -2\mu_{i,j+\frac{1}{2}}^n \epsilon_{z_{i,j+\frac{1}{2}}}^n + \frac{2}{3}\mu_{i,j+\frac{1}{2}}^n \epsilon_{i+1,j+1}^n \quad (104)$$

$$\tau_{\theta\theta_{i+\frac{1}{2},j}}^n = -2\mu_{i+\frac{1}{2},j}^n \epsilon_{\theta_{i+\frac{1}{2},j}}^n + \frac{2}{3}\mu_{i+\frac{1}{2},j}^n \epsilon_{i+1,j+1}^n \quad (105)$$

$$\tau_{rz_{i+\frac{1}{2},j+\frac{1}{2}}}^n = -\mu_{i+\frac{1}{2},j+\frac{1}{2}}^n \epsilon_{rz_{i+1,j+1}}^n \quad (106)$$

and for turbulent flow, the first three viscous stresses are zero and employing an eddy viscosity:

$$\tau_{rz}^n_{i+1/2, j+1/2} = -(\mu_{i+1/2, j+1/2} + \mu_{\lambda E}^n) \epsilon_{rz}^n_{i+1, j+1} \quad (107)$$

If the magnetic induction equations are employed, the stresses become

$$\tau_{rr}^n_{i+1/2, j} = \frac{B_{r, i+1/2, j}^n \cdot B_{r, i+1/2, j}^n}{\mu_p} + \text{viscous component} \quad (108)$$

$$\tau_{zz}^n_{i, j+1/2} = \frac{B_{z, i, j+1/2}^n \cdot B_{z, i, j+1/2}^n}{\mu_p} + \text{viscous component} \quad (109)$$

$$\tau_{\theta\theta}^n_{i+1/2, j} = \frac{B_{\theta, i+1/2, j}^n \cdot B_{\theta, i+1/2, j}^n}{\mu_p} + \text{viscous component} \quad (110)$$

$$\tau_{rz}^n_{i+1/2, j+1/2} = \frac{B_{r, i+1/2, j+1/2}^n \cdot B_{z, i+1/2, j+1/2}^n}{\mu_p} + \text{viscous component} \quad (111)$$

The change in velocities over a time step results from forces due to pressure, magnetic fields and gravity.

$$u_{i, j}^{n+1} = u_{i, j}^n - \frac{\Delta t^{n+1/2}}{\rho_{i, j}^n} \left\{ \frac{p_{i, j+1/2}^{n+1/2} - p_{i, j-1/2}^{n+1/2}}{\Delta z_j} \right\} - g_z \Delta t^{n+1/2} - \frac{\Delta t^{n+1/2}}{\rho_{i, j}^n} \left\{ \frac{r_{i+1/2} \tau_{rz}^n_{i-1/2, j+1/2} - r_{i-1/2} \tau_{rz}^n_{i-1/2, j-1/2}}{r_i \cdot \Delta r_i} \right. \\ \left. + \frac{\tau_{zz}^n_{i, j+1/2} - \tau_{zz}^n_{i, j-1/2}}{\Delta z_j} \right\} + j_z^{n+1/2} \frac{B_{\theta, i, j}^n}{\rho_{i, j}^n} \frac{\Delta t^{n+1/2}}{\rho_{i, j}^n} \quad (112)$$

$$\begin{aligned}
 v_{i,j}^{n+1} = & v_{i,j}^n - \frac{\Delta t^{n+1/2}}{\rho_{i,j}^n} \left\{ \frac{p_{i+1/2,j}^{n+1/2} - p_{i-1/2,j}^{n+1/2}}{\Delta r_i} \right\} - g_r \Delta t^{n+1/2} - \frac{\Delta t^{n+1/2}}{\rho_{i,j}^n} \left\{ \frac{r_{i+1/2} \tau_{rr}^n - r_{i-1/2} \tau_{rr}^n}{r_i \cdot \Delta r_i} \right. \\
 & + \frac{\tau_{rz}^n}{\Delta z_j} \left. \frac{i+1/2, j+1/2 - \tau_{rz}^n}{i-1/2, j-1/2} - \frac{\tau_{\theta\theta}^n}{p_{i-1/2, j+1/2}^n} \frac{i+1/2, j + \tau_{\theta\theta}^n}{i-1/2, j} \right\} + j_{z,i,j}^{n+1/2} B_{\theta,i,j}^n \frac{\Delta t^{n+1/2}}{\rho_{i,j}^n} \quad (113)
 \end{aligned}$$

The change in energy for each volume element over a time step is based on contributions from: (1) the work done by the pressure of the surroundings on the volume element, (2) the work done by viscous and/or magnetic forces on a volume element, (3) the energy input by thermal conduction into a volume element, (4) the work done by the pondermotive (Lorentz) force in driving the fluid, including Joule heating and (5) the work done by gravity. Note, once again, if the stress elements contain magnetic terms ($Re_m \gg 1$) then the last terms in Equation (112) and (113) are ignored.

$$e_{i,j}^n = e_{i,j}^n - \frac{1}{2} (u_{i,j}^n \cdot u_{i,j}^n + v_{i,j}^n \cdot v_{i,j}^n) \quad (114)$$

$$Dr_{i+1/2} = \frac{r_{i+1/2}}{(r_{i+1} - r_i) r_i \Delta r_i} \quad (115)$$

$$Dr_{i-1/2} = \frac{r_{i-1/2}}{(r_i - r_{i-1/2}) r_i \Delta r_i} \quad (116)$$

$$Dz_{j+1/2} = \frac{1}{(z_{j+1} - z_j) \Delta z_j} \quad (117)$$

$$Dz_{j-1/2} = \frac{1}{(z_j - z_{j-1}) \Delta z_j} \quad (118)$$

$$\begin{aligned}
 e_{i,j}^{n+1} = e_{i,j}^n & - \frac{\Delta t^{n+1/2}}{\rho_{i,j}^n} \left\{ \frac{r_{i+1/2} \cdot p_{i+1/2,j}^{n+1/2} \cdot v_{i+1/2,j}^{n+1/2} - r_{i-1/2} \cdot p_{i-1/2,j}^{n+1/2} \cdot v_{i-1/2,j}^{n+1/2}}{r_i \Delta r_i} + \right. \\
 & \frac{p_{i,j+1/2}^{n+1/2} \cdot u_{i,j+1/2}^{n+1/2} - p_{i,j-1/2}^{n+1/2} \cdot u_{i,j-1/2}^{n+1/2}}{\Delta z_j} \left. - \frac{\Delta t^{n+1/2}}{\rho_{i,j}^n} \left\{ \frac{r_{i+1/2} \cdot \tau_{rr_{i+1/2,j}}^n \cdot v_{i+1/2,j}^{n+1/2} - r_{i-1/2} \cdot \tau_{rr_{i-1/2,j}}^n \cdot v_{i-1/2,j}^{n+1/2}}{r_i \Delta r_i} \right. \right. \\
 & + \frac{r_{i+1/2} \cdot \tau_{rz_{i+1/2,j+1/2}}^n \cdot u_{i+1/2,j}^{n+1/2} - r_{i-1/2} \cdot \tau_{rz_{i-1/2,j-1/2}}^n \cdot u_{i-1/2,j}^{n+1/2}}{r_i \Delta r_i} \\
 & \left. + \frac{\tau_{rz_{i+1/2,j+1/2}}^n \cdot v_{i,j+1/2}^{n+1/2} - \tau_{rz_{i-1/2,j-1/2}}^n \cdot v_{i,j-1/2}^{n+1/2}}{\Delta z_j} + \frac{\tau_{zz_{i,j+1/2}}^n \cdot u_{i,j+1/2}^{n+1/2} - \tau_{zz_{i,j-1/2}}^n \cdot u_{i,j-1/2}^{n+1/2}}{\Delta z_j} \right\} \\
 & + \frac{c \Delta t^{n+1/2}}{\rho_{i,j}^{n+1/2}} \left\{ \left[Dr_{i+1/2} \cdot \frac{i_{i+1/2,j}^{n+1/2}}{c_v} \cdot \lambda_{i+1/2,j} + Dr_{i-1/2} \cdot \frac{i_{i-1/2,j}^{n+1/2}}{c_v} \cdot \lambda_{i-1/2,j} \right] + \left[Dz_{j+1/2} \cdot \frac{i_{i,j+1/2}^{n+1/2}}{c_v} \cdot \lambda_{i,j+1/2} \right. \right. \\
 & \left. \left. + Dz_{j-1/2} \cdot \frac{i_{i,j-1/2}^{n+1/2}}{c_v} \cdot \lambda_{i,j-1/2} \right] \right\} + \left(j_{z_{i,j}}^{n+1/2} E_{z_{i,j}}^{n+1/2} + j_{r_{i,j}}^{n+1/2} E_{r_{i,j}}^{n+1/2} \right) \frac{\Delta t^{n+1/2}}{\rho_{i,j}^n} - (v_{i,j}^{n+1} \cdot g_r + u_{i,j}^{n+1} \cdot g_z) \Delta t^{n+1/2}
 \end{aligned} \tag{119}$$

Problems where the induced field becomes significant ($Re_m \gg 1$)

requires a solution to the induction equations:

$$\begin{aligned}
 B_{\theta,i,j}^{n+1} = B_{\theta,i,j}^n & + \frac{\Delta t^{n+1/2}}{\mu_p} \left\{ Dr_{i+1/2} \left[\frac{B_{\theta,i,j+1}^n}{\sigma_{i,j+1/2}^n} - \frac{B_{\theta,i,j}^n}{\sigma_{i,j+1/2}^n} \right] + Dr_{i-1/2} \left[\frac{B_{\theta,i-1,j}^n}{\sigma_{i-1/2,j}^n} - \frac{B_{\theta,i,j}^n}{\sigma_{i-1/2,j}^n} \right] + \right. \\
 & \left. Dz_{j+1/2} \left[\frac{B_{\theta,i+1,j}^n}{\sigma_{i+1/2,j}^n} - \frac{B_{\theta,i,j}^n}{\sigma_{i+1/2,j}^n} \right] + Dz_{j-1/2} \left[\frac{B_{\theta,i,j-1}^n}{\sigma_{i,j-1/2}^n} - \frac{B_{\theta,i,j}^n}{\sigma_{i,j-1/2}^n} \right] \right\}
 \end{aligned} \tag{120}$$

$$\begin{aligned}
B_{z,i,j}^{n+1} &= B_{z,i,j}^n + \frac{\Delta t^{n+1/2}}{\mu_p} \left\{ \text{Dr}_{i+1/2} \left[\frac{B_{z,i,j+1}^n}{\sigma_{i,j+1/2}^n} - \frac{B_{z,i,j}^n}{\sigma_{i,j+1/2}^n} \right] + \text{Dr}_{i-1/2} \left[\frac{B_{z,i-1,j}^n}{\sigma_{i-1/2,j}^n} - \frac{B_{z,i,j}^n}{\sigma_{i-1/2,j}^n} \right] + \right. \\
&\quad \left. \text{Dz}_{j+1/2} \left[\frac{B_{z,i+1,j}^n}{\sigma_{i+1/2,j}^n} - \frac{B_{z,i,j}^n}{\sigma_{i+1/2,j}^n} \right] + \text{Dr}_{i-1/2} \left[\frac{B_{\theta,i,j-1}^n}{\sigma_{i,j-1/2}^n} - \frac{B_{z,i,j}^n}{\sigma_{i,j-1/2}^n} \right] \right\} \quad (121)
\end{aligned}$$

$$\begin{aligned}
B_{r,i,j}^{n+1} &= B_{r,i,j}^n + \frac{\Delta t^{n+1/2}}{\mu_p} \left\{ \text{Dr}_{i+1/2} \left[\frac{B_{r,i,j+1}^n}{\sigma_{i,j+1/2}^n} - \frac{B_{r,i,j}^n}{\sigma_{i,j+1/2}^n} \right] + \text{Dr}_{i-1/2} \left[\frac{B_{r,i-1,j}^n}{\sigma_{i-1/2,j}^n} - \frac{B_{r,i,j}^n}{\sigma_{i-1/2,j}^n} \right] + \right. \\
&\quad \left. \text{Dz}_{j+1/2} \left[\frac{B_{r,i+1,j}^n}{\sigma_{i+1/2,j}^n} - \frac{B_{r,i,j}^n}{\sigma_{i+1/2,j}^n} \right] + \text{D} \left[\frac{B_{r,i,j-1}^n}{\sigma_{i,j-1/2}^n} - \frac{B_{r,i,j}^n}{\sigma_{i,j-1/2}^n} \right] \right\} \quad (122)
\end{aligned}$$

Problems where $\text{Re}_m \ll 1$, such as an MHD generator, require solution to Equation (53).

Solutions to the Elliptic PDE for Small Re_m

There are numerous numerical approaches to solving Equation (53). Three methods were considered: Alternating direction implicit (ADI), Gauss-Seidel (GS) and Successive Over-Relaxation (SOR). SOR was found to converge more rapidly in all cases and therefore was the most promising. Once Equation (53) is solved for ϕ or Ψ , the electric fields and currents are determined and the pondermotive force ($\vec{j} \times \vec{B}$) and electric energy ($\vec{j} \cdot \vec{E}$) become known quantities in the momentum and energy equations. Computation of a new fluid dynamics state will influence the behavior of currents which result in a "coupled solution" necessitating solving Equation (53) frequently if currents are strongly dependent on the flow field or infrequently if the currents are weakly dependent on the flow field.

A discussion of the solution of Equation (53) by ADI, GS or SOR follows. ADI has already been employed to solve the thermal magnetic diffusion described by Equations (49) through (51) and (36).

In the MHD generator under consideration, the magnetic field is time independent, thus satisfying Equations (54) and (55) identically. A time dependent (induced) magnetic field which is frozen to the fluid and/or diffusing into the neighboring medium would create a time dependent potential (or stream current) term in Equation (53). In this case, it would be necessary to solve the magnetic induction Equations (49) through (51).

Considering the ADI method, the numerical solution to Equation (53) was performed implicitly by "sweeping" along the axial and radial (or Cartesian) coordinates and summing the contributions of gradients in both directions. Expressing the derivatives in terms of finite difference expressions, summing, and rearranging, a series of simultaneous algebraic equations results. The coefficient matrix of the dependent variable representing these algebraic equations is in tri-diagonal form and is expeditiously inverted without the need for iteration. The matrix is decomposed into upper and lower matrices and solved exactly equation by equation. The (zeroth) first and second derivatives (in the z-direction) are cast in the following finite difference expressions:*

$$\frac{\delta}{\delta z}(\phi_{i,j}) = \phi_{i,j+\frac{1}{2}}\left[\frac{1}{\Delta z_j}\right] - \phi_{i,j-\frac{1}{2}}\left[\frac{1}{\Delta z_j}\right] \quad (123)$$

* ψ replaces ϕ if Equation (66) is to be solved instead of (63).

$$\frac{\delta}{\delta z} \left[\frac{\delta}{\delta z} (\phi_{i,j}) \right] = \frac{1}{\Delta z_j} \left[\left(\frac{\phi_{i,j+\frac{1}{2}} - \phi_{i,j}}{z_{j+1} - z_j} \right) - \left(\frac{\phi_{i,j} - \phi_{i,j-\frac{1}{2}}}{z_j - z_{j-1}} \right) \right] \quad (124)$$

$$\frac{\delta}{\delta z} [\ln(\sigma_{+})] = \frac{1}{\sigma_{+i,j}} \frac{1}{\Delta z_j} (\sigma_{+i,j+\frac{1}{2}} - \sigma_{+i,j-\frac{1}{2}}) \quad (125)$$

$$\frac{\delta}{\delta z} (\beta) = \frac{1}{\Delta z_j} (\beta_{i,j+\frac{1}{2}} - \beta_{i,j-\frac{1}{2}}) \quad (126)$$

$$\begin{aligned} \frac{\delta}{\delta z} (vB + \beta uB) = \frac{1}{\Delta z_j} [& (v_{i,j+\frac{1}{2}} \cdot B_{i,j+\frac{1}{2}} + \beta_{i,j+\frac{1}{2}} \cdot u_{i,j+\frac{1}{2}} \cdot B_{i,j+\frac{1}{2}}) - \\ & (v_{i,j-\frac{1}{2}} \cdot B_{i,j-\frac{1}{2}} + \beta_{i,j-\frac{1}{2}} \cdot v_{i,j-\frac{1}{2}} \cdot B_{i,j-\frac{1}{2}})] \end{aligned} \quad (127)$$

Equation (53) becomes in finite difference form:

$$A_j \phi_{i,j+\frac{1}{2}} + B_j \phi_{i,j} + C_j \phi_{i,j-\frac{1}{2}} = D_j \quad (128)$$

for the i,jth cell. Sweeping across the jth row, j simultaneous equations result. In relaxing to the steady state solution: the left-hand side of Equation (53) was set = to $(\phi(\text{new}) - \phi(\text{old})) / \Delta t$ and iterations proceeded until $\phi(\text{new}) = \phi(\text{old})$ or the right-hand side of Equation (53) was equal to zero.

$$A_3 \phi_4 + B_3 \phi_3 + C_3 \phi_2 = D_3 \quad (129)$$

$$A_2 \phi_3 + B_2 \phi_2 + \phi_1 = D_2 \quad (130)$$

$$A_1 \phi_2 + B_1 \phi_1 = D_1 \quad (131)$$

where the coefficients A(j), B(j), C(j) and D(j) are:

$$\begin{aligned} A_j = & \frac{1}{(z_{j+1} - z_j) \Delta z_j} + \frac{1}{\Delta z_j} \left[\frac{1}{\sigma_{+i,j}} \left(\frac{\sigma_{+i,j+\frac{1}{2}} - \sigma_{+i,j-\frac{1}{2}}}{\Delta z_j} \right) + \frac{\beta_{i,j}}{\sigma_{+i,j}} \right. \\ & \left. \left\{ \left(\frac{\sigma_{+i+\frac{1}{2},j} - \sigma_{+i-\frac{1}{2},j}}{\Delta r_i} \right) + \left(\frac{\beta_{j+\frac{1}{2},j} - \beta_{i-\frac{1}{2},j}}{\Delta r_i} \right) \right\} \right] \end{aligned} \quad (132)$$

$$B_j = \left[-\frac{1}{(z_{j+1}-z_j)\Delta z_j} - \frac{1}{(z_{j-1}-z_j)\Delta z_j} \right] \frac{1}{\Delta t} \quad (133)$$

$$C_j = \frac{1}{(z_{j-1}-z_j)\Delta z_j} - \frac{1}{\Delta z_j} \left[\frac{\sigma_{+i,j+1/2} - \sigma_{+i,j-1/2}}{\Delta z_j} + \frac{\beta_{i,j}}{\sigma_{+i,j}} \right. \\ \left. \left\{ \left(\frac{\sigma_{+i+1/2,j} - \sigma_{+i-1/2,j}}{\Delta r_i} \right) + \left(\frac{\beta_{i+1/2,j} - \beta_{i-1/2,j}}{\Delta r_i} \right) \right\} \right] \quad (134)$$

$$D_j = -[v_{i,j} \cdot B_{i,j} + \beta_{i,j} \cdot u_{i,j} \cdot B_{i,j}] \frac{1}{\sigma_{+i,j}} \frac{1}{\Delta z_j} (\sigma_{+i,j+1/2} - \sigma_{+i,j-1/2}) \quad (135)$$

Similar relations are developed for the column sweep. The solution to ϕ occurs when the potential has relaxed to its steady state value and no discernible change in ϕ occurs in ensuing iterations.

The G-S technique relaxes to a numerical solution by use of the algorithm:

$$\phi_{i,j}^{n+1} = \phi_{i,j}^n + (-D_i - D_j + A_i \phi_{i+1,j}^n + A_j \phi_{i,j+1}^n + C_i \phi_{i-1,j}^n + C_j \phi_{i,j-1}^n) / (B_i + B_j) \quad (136)$$

or

$$\psi_{i,j}^{n+1} = \psi_{i,j}^n + (-D_i - D_j + A_i \psi_{i+1,j}^n + A_j \psi_{i,j+1}^n + C_i \psi_{i-1,j}^n + C_j \psi_{i,j-1}^n) / (B_i + B_j) \quad (137)$$

where axial coefficients A_j , B_j , C_j and D_j are defined by Eqns. (132)-(135) and radial coefficients A_i , B_i , C_i and D_i are derived in the same manner.

SOR employs the GS method, with acceleration to convergence achieved by employing the modified algorithm:

$$\phi_{i,j}^{n+1} = \omega \phi_{i,j}^n + (1-\omega) \phi_{i,j}^{n+1} \quad (138)$$

or

$$\Psi_{i,j}^{n+1} = \omega \Psi_{i,j}^n + (1-\omega) \Psi_{i,j}^n \quad (139)$$

where $\omega = 1.75$ ($\omega = 0$ yields the g-s method).

Oliver (58) discusses the influence of electromagnetic properties on the rate of convergence and suggests, in some cases, under-relaxation ($\omega = 0.2$). SOR was found to converge more rapidly than GS or ADI and thus was the method employed to solve Eqn (53).

Results of a variety of problems are presented in section (3.5).

ϕ or Ψ Boundary Conditions

The electrical boundary conditions on the electrodes as derived in Appendix (A.2) are:

$$\frac{\delta}{\delta r}(\Psi) = \beta \frac{\delta}{\delta z}(\Psi); \quad \frac{\delta}{\delta z}(\phi) = 0: \text{conductor} \quad (140)$$

$$\frac{\delta}{\delta r}(\phi) = -\beta \frac{\delta}{\delta z}(\phi); \quad \frac{\delta}{\delta z}(\Psi) = 0: \text{insulator} \quad (141)$$

Equation (53) is completely described by the boundary conditions. In addition, the electrical relation between the generator (internal circuit) and external circuit must be specified in order to provide a complete set of boundary conditions necessary for solving the elliptic partial differential equation. The particular generator, e.g., Faraday, Hall, Diagonal,* etc., determines the nature of the boundary conditions employed and further furnishes impetus for employing either ϕ or Ψ , in order to determine the electric field and currents.

*The primary difference between the Faraday, Hall and Diagonal generator is the alignment of the electrode-pairs in the MHD channel.

The difficult boundary condition to specify occurs at infinity, but for the Faraday generator, the stream current function is used since at

$$z = \infty, \Psi = \Psi_{\infty} = 0 \quad (142)$$

and is constant up to the first electrode. For the Hall generator, use is made of the potential because at

$$z = \infty, \phi = \phi_{\infty} = A \quad (143)$$

is known, and is constant up to the first insulator.

Appendix (A.2) contains an in-depth discussion and derivation of the electrical boundary conditions in both the electric potential and stream current function.

Phase II (Eulerian Frame of Reference)

Once the new velocities are known, the convective terms in the differential equations can be computed by transporting mass from a cell

$$i^* = i(v_{i+\frac{1}{2},j}^{n+1} > 1), i' = i+1(v_{i+\frac{1}{2},j}^{n+1} < 1) \quad (144)$$

$$j' = j(u_{i,j+\frac{1}{2}}^{n+1} > 1), j^* = j+1(u_{i,j+\frac{1}{2}}^{n+1} < 1) \quad (145)$$

$$\rho_{i+\frac{1}{2},j}^{n+1} = \rho_{i',j}^n \left\{ 1 - \frac{\Delta t^{n+1}}{r_{i+\frac{1}{2}}} \cdot \frac{r_{i+1} v_{i+1,j}^{n+1} - r_i v_{i,j}^{n+1}}{r_{i+1} - r_i} \right\} \quad (146)$$

$$\rho_{i,j+\frac{1}{2}}^{n+1} = \rho_{i,j}^n \left\{ 1 - \Delta t^{n+1} \cdot \frac{u_{i,j+1}^{n+1} - u_{i,j}^{n+1}}{z_{j+1} - z_j} \right\} \quad (147)$$

to its neighbors. In Equations (146) and (147), the densities are updated, based on the velocities. The mass fluxes are computed in Equations (148) and (149) and based on these values, the momentum, energy and magnetic transport values are computed in Equations (150) through (161).

$$F_{m_{i+\frac{1}{2}}}^{n+1} = v_{i+\frac{1}{2},j}^{n+1} \cdot \rho_{i+\frac{1}{2},j}^{n+1} \cdot 2 \cdot \pi \cdot r_{i+\frac{1}{2}} \left(1 + \frac{1}{2} \cdot v_{i+\frac{1}{2},j}^{n+1} \Delta t^{n+1}\right) \cdot \Delta z_j \cdot \Delta t^{n+1} \quad (148)$$

$$F_{m_{j+\frac{1}{2}}}^{n+1} = u_{i,j+\frac{1}{2}}^{n+1} \cdot \rho_{i,j+\frac{1}{2}}^{n+1} \cdot 2 \cdot \pi \cdot r_i \left(1 + \frac{1}{2} \cdot u_{i,j+\frac{1}{2}}^{n+1} \Delta t^{n+1}\right) \cdot \Delta r_i \cdot \Delta t^{n+1} \quad (149)$$

$$F_{u_{i+\frac{1}{2}}}^{n+1} = F_{m_{i+\frac{1}{2}}}^{n+1} \cdot u_{i',j}^{n+1} \quad (150)$$

$$F_{v_{i+\frac{1}{2}}}^{n+1} = F_{m_{i+\frac{1}{2}}}^{n+1} \cdot v_{i',j}^{n+1} \quad (151)$$

$$F_{u_{j+\frac{1}{2}}}^{n+1} = F_{m_{j+\frac{1}{2}}}^{n+1} \cdot u_{i,j'}^{n+1} \quad (152)$$

$$F_{v_{j+\frac{1}{2}}}^{n+1} = F_{m_{j+\frac{1}{2}}}^{n+1} \cdot v_{i,j'}^{n+1} \quad (153)$$

$$F_{e_{i+\frac{1}{2}}}^{n+1} = F_{m_{i+\frac{1}{2}}}^{n+1} \cdot e_{i',j}^{n+1} \quad (154)$$

$$F_{e_{j+\frac{1}{2}}}^{n+1} = F_{m_{j+\frac{1}{2}}}^{n+1} \cdot e_{i,j'}^{n+1} \quad (155)$$

$$m_{r_{i+\frac{1}{2}}}^{n+1} = \frac{v_{i,j+\frac{1}{2}}^{n+1} \cdot B_{z_{i,j+\frac{1}{2}}}^{n+1} \cdot \Delta t^{n+1}}{z_{j+1} - z_j} \quad (156)$$

$$m_{r_{j+\frac{1}{2}}}^{n+1} = \frac{u_{i,j+\frac{1}{2}}^{n+1} \cdot B_{r_{i,j'}}^{n+1} \cdot \Delta t^{n+1}}{z_{j+1} - z_j} \quad (157)$$

$$m_{z_{i+\frac{1}{2}}}^{n+1} = \frac{v_{i+\frac{1}{2},j}^{n+1} \cdot B_{z_{i',j}}^{n+1} \cdot \Delta t^{n+1}}{r_{i+1} - r_i} \quad (158)$$

$$m_{z_{j+\frac{1}{2}}}^{n+1} = \frac{u_{i+\frac{1}{2},j}^{n+1} \cdot B_{r_{i+\frac{1}{2},j}}^{n+1} \cdot \Delta t^{n+1}}{r_{i+1} - r_i} \quad (159)$$

$$m_{\theta_{i+\frac{1}{2}}}^{n+1} = \frac{v_{i+\frac{1}{2},j}^{n+1} \cdot B_{\theta_{i,j}}^{n+1} \cdot \Delta t^{n+1}}{r_{i+1} - r_i} \quad (160)$$

$$m_{\theta_{j+\frac{1}{2}}}^{n+1} = \frac{u_{i,j+\frac{1}{2}}^{n+1} \cdot B_{\theta_{i,j}}^{n+1} \cdot \Delta t^{n+1}}{z_{j+1} - z_j} \quad (161)$$

Finally, the new mass, density, velocities, energy and magnetic fields are computed at time (n+1) at the center of each cell based on the convection terms in phase II and force terms in phase I.

$$M_{i,j}^{n+1} = M_{i,j}^n + F_{m_{i-\frac{1}{2}}}^{n+1} + F_{m_{j-\frac{1}{2}}}^{n+1} - F_{m_{i+\frac{1}{2}}}^{n+1} - F_{m_{j+\frac{1}{2}}}^{n+1} \quad (162)$$

$$\rho_{i,j}^{n+1} = \frac{M_{i,j}^{n+1}}{\pi(r_{i+\frac{1}{2}}^2 - r_{i-\frac{1}{2}}^2) \Delta z_j} \quad (163)$$

$$u_{i,j}^{n+1} = \frac{u_{i,j}^{n+1} \cdot M_{i,j}^n + F_{u_{i-\frac{1}{2}}}^{n+1} + F_{u_{j-\frac{1}{2}}}^{n+1} - F_{u_{i+\frac{1}{2}}}^{n+1} - F_{u_{j+\frac{1}{2}}}^{n+1}}{M_{i,j}^{n+1}} \quad (164)$$

$$v_{i,j}^{n+1} = \frac{v_{i,j}^{n+1} \cdot M_{i,j}^n + F_{v_{i-\frac{1}{2}}}^{n+1} + F_{v_{j-\frac{1}{2}}}^{n+1} - F_{v_{i+\frac{1}{2}}}^{n+1} - F_{v_{j+\frac{1}{2}}}^{n+1}}{M_{i,j}^{n+1}} \quad (165)$$

$$e_{i,j}^{n+1} = \frac{e_{i,j}^{n+1} \cdot M_{i,j}^n + F_{e_{i-\frac{1}{2}}}^{n+1} + F_{e_{j-\frac{1}{2}}}^{n+1} - F_{e_{i+\frac{1}{2}}}^{n+1} - F_{e_{j+\frac{1}{2}}}^{n+1}}{M_{i,j}^{n+1}} \quad (166)$$

$$B_{r_{i,j}}^{n+1} = B_{r_{i,j}}^{n+1} + {}^m r_{j-\frac{1}{2}}^{n+1} - {}^m r_{i-\frac{1}{2}}^{n+1} - {}^m r_{i+\frac{1}{2}}^{n+1} + {}^m r_{j+\frac{1}{2}}^{n+1} \quad (167)$$

$$B_{z_{i,j}}^{n+1} = B_{z_{i,j}}^{n+1} + {}^m z_{j-\frac{1}{2}}^{n+1} - {}^m z_{i-\frac{1}{2}}^{n+1} - {}^m z_{j+\frac{1}{2}}^{n+1} + {}^m z_{j+\frac{1}{2}}^{n+1} \quad (168)$$

$$B_{\theta_{i,j}}^{n+1} = B_{\theta_{i,j}}^{n+1} + {}^m \theta_{j-\frac{1}{2}}^{n+1} + {}^m \theta_{i-\frac{1}{2}}^{n+1} - {}^m \theta_{i+\frac{1}{2}}^{n+1} - {}^m \theta_{j+\frac{1}{2}}^{n+1} \quad (169)$$

III. DISCUSSION AND APPLICATION OF PHENOMENA INDUCED BY HYDRODYNAMIC, VISCOUS OR ELECTROMAGNETIC FORCES

The effectiveness of a numerical procedure is measured by its ability to reproduce the results of experiments or classical analytical solutions. In this section, there are a variety of problems solved numerically which illustrate some fundamental physical process influencing the behavior of an electrically conducting fluid. In each case, the numerical results were compared with experimental data or a closed form analytic solution. Once established that the technique can solve the classic problems, the more challenging applications are considered.

Problems are categorized into five areas: shocks, boundary layers, compressible flow, diffusion and Emf forces. Each subsection details the make-up and solution of the particular problem being investigated.

3.1 Shocks

Shocks were examined in a variety of problems: supersonic flow over a sharp-nosed projectile, shock tube flow with and without magnetic fields, regular-irregular (Mach) reflection generated by flow over a wedge, supersonic flow over a semi-infinite cylinder and hypersonic flow over a blunt-nose re-entry vehicle.

A test was run and compared with HULL to check out the hydrodynamic logic. A shock tube containing a diaphragm separating a low pressure region (40 atm) from a high pressure region (4,000 atm) was modeled.

After bursting of the diaphragm, calculations proceeded employing both programs and the results were identical in both cases. Referring to Figure (9), a shock was initiated from a pressure ratio of 100 generating a particle velocity of $1.5 \cdot 10^6$ cm/sec. Under the severe pressure gradient introduced by this test, no evidence of any numerical instability occurred. This shock tube problem is explored in greater depth later in this section.

A problem of interest to the aerodynamicist is shock attachment or detachment over a sharp-nosed projectile. Considering projectiles of nose angles of 20° , 35° and 45° in a Mach three airstream, attached and detached shocks were generated. Further, by changing the free stream Mach number, the shock can be re-attached. Figure (10) shows an attached shock at Mach three and angle 20° . Increasing the nose angle to 35° , the shock begins to detach. At 45° , the shock is further displaced from the body. Decreasing the Mach number to two (30°), the shock originally attached, detaches, as seen in Figure (11). Results compare favorably with theory (89), which predicts shock angles of 37° and 62° for nose angles of 20° and 35° as compared with shock angles of 39° and 58° developed numerically.

Referring to Figure (12), further analysis of the shock system reveals that initially a shock (compression) occurs followed by an expansion about the wedge turning point. For a fixed inlet Mach number, the angle of the projectile nose determines the location and direction of the oblique shock. As the projectile nose exceeds a critical angle, a normal shock develops in the vicinity of the projectile nose and detaches a distance depending on the inlet Mach number and nose angle.

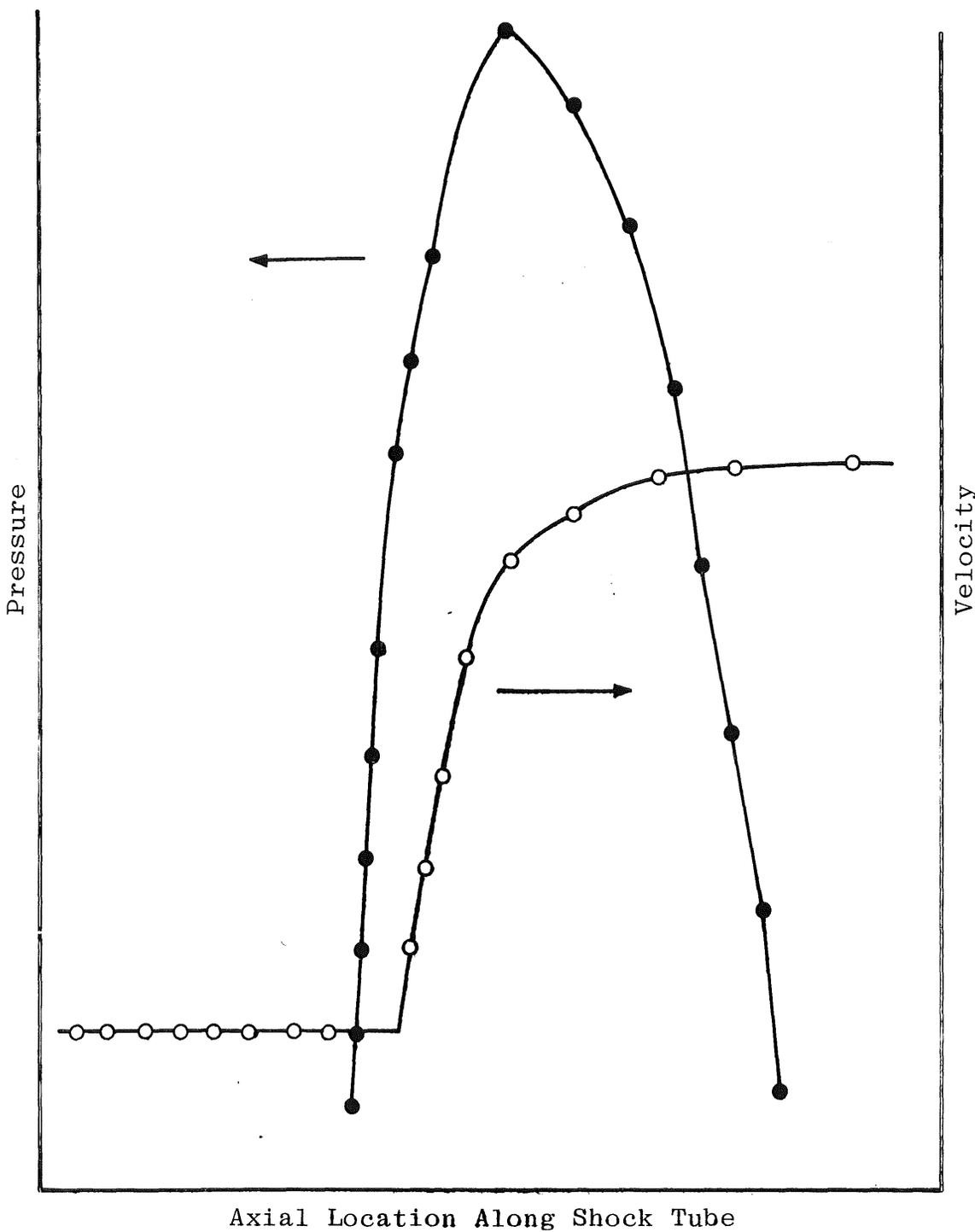


Fig. 9 Comparison of Computer Programs for Shock Tube Test Case

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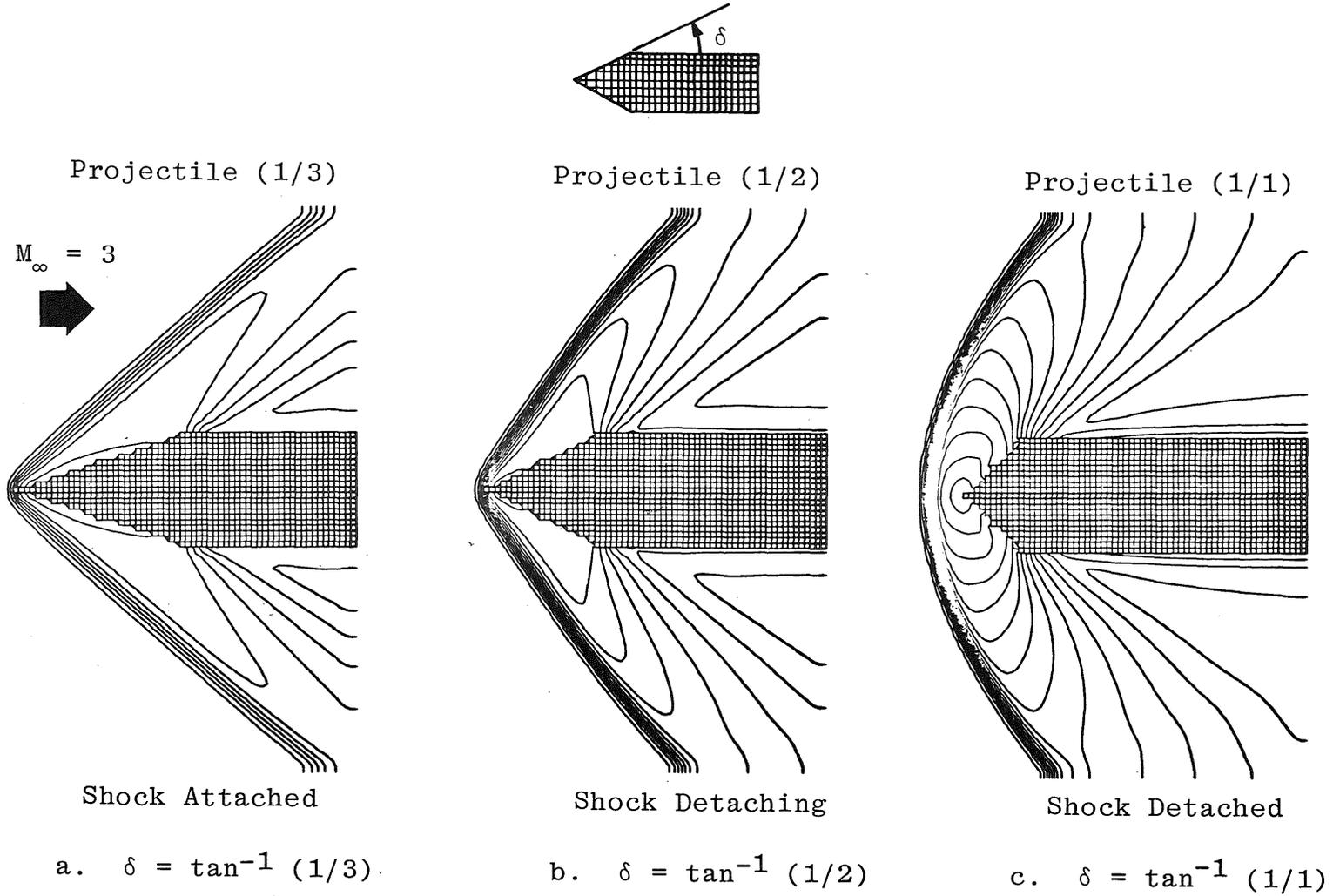


Fig. 10 Sharp-Nosed Projectiles of Angles 20° , 35° , and 45°

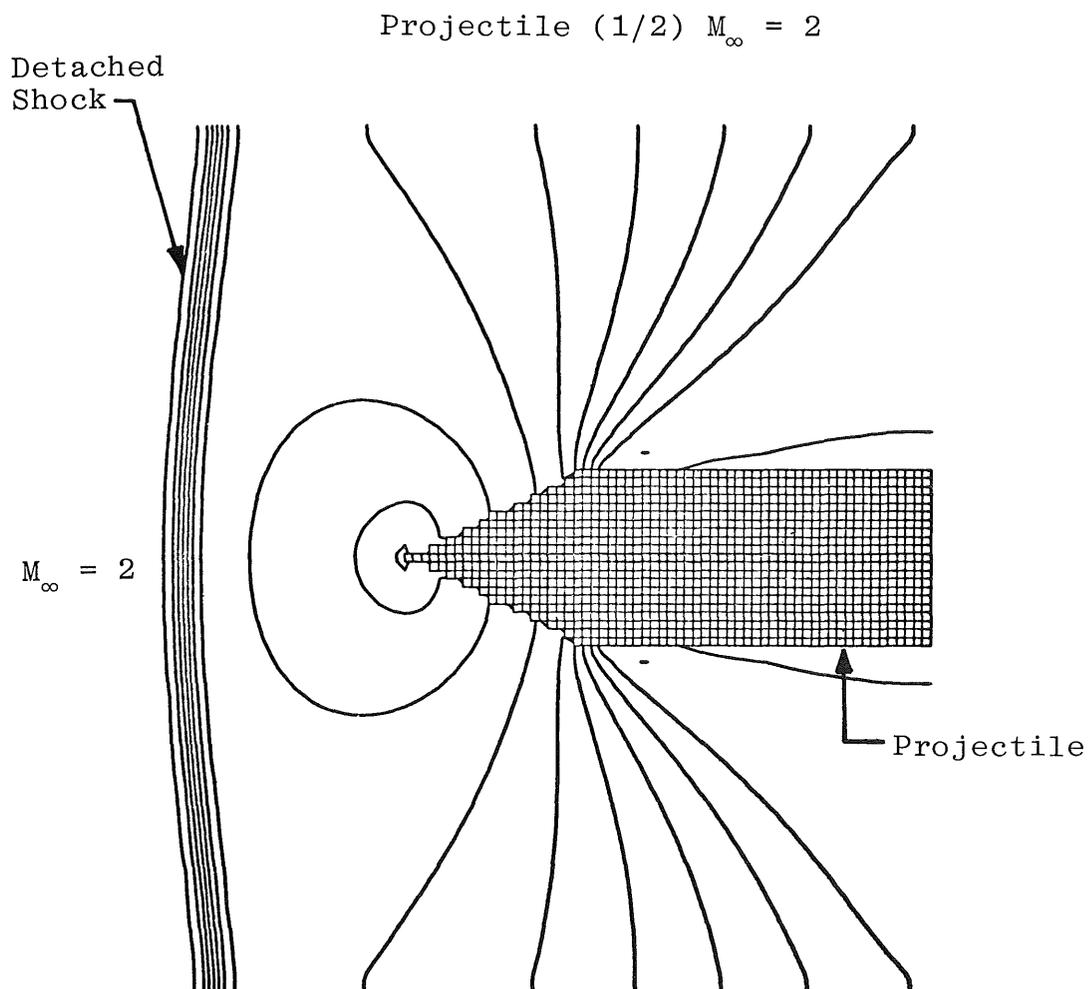


Fig. 11 Detached Shock for a 30° Wedge

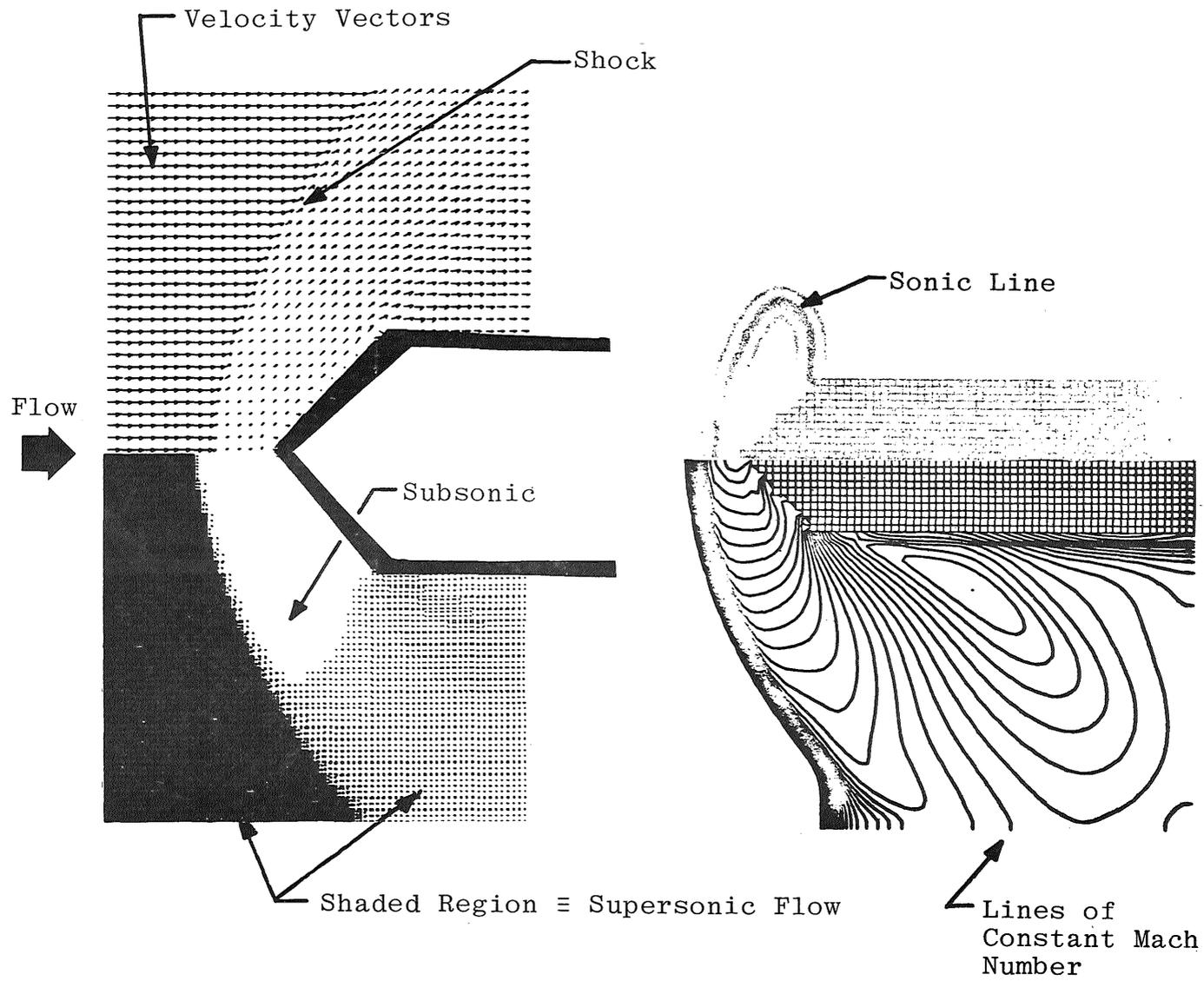


Fig. 12 Sonic Line for a 48° Wedge

The normal or strongly oblique detached shock compresses the flow from supersonic to subsonic conditions. However as the flow expands, a sonic condition (sonic line in Figure (12)) is reached, wherein the flow once again becomes supersonic. Although this problem presents no special challenge to a transient explicit finite difference procedure, other techniques, such as the method of characteristics, etc., cannot treat both the subsonic and supersonic regimes. Figure (13) illustrates a detached shock for a 45° wedge and Figure (14) depicts the transient formation of an attached shock over a 20° wedge.

In the early 1960's (65), studies were performed to determine the feasibility of employing magnetic fields to control highly ionized, conducting external flow fields. Applying a magnetic field of 0-1 Tesla to the projectile (20°) already computed, and assuming infinite conductivity, the shock was made to detach from the body. Initially, a magnetic field of 0.5 Tesla distorted the shock (Figure (15)) and increasing the magnetic field to 0.75 Tesla caused detachment. A magnetic field of 1 Tesla further detaches the shock. Vehicle weight limitations prohibited use of onboard magnets to actually attain this objective.

Shock Tube

Employing a less severe pressure gradient, numerical results were compared with shock tube theory and the Rankine-Hugoniot equations. Referring to Figure (16a) and Equations (170) to (172), a pressure

$$u_p = u_1 - u_2 = C_s \left(1 - \frac{u_2}{u_1}\right) \quad (170)$$

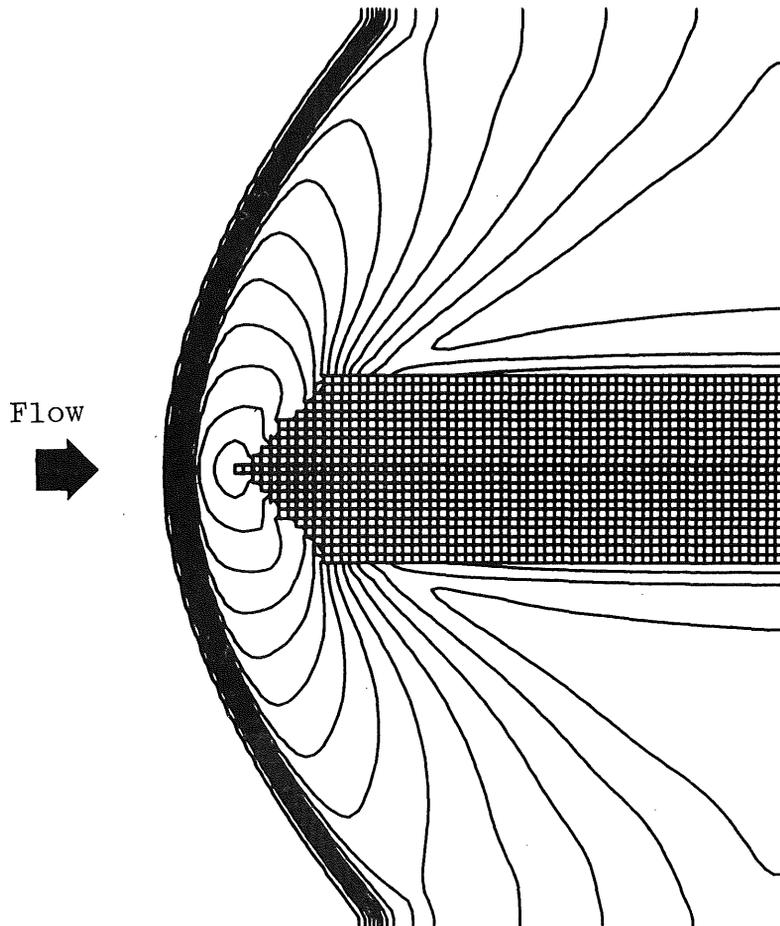


Fig. 13 Detached Shock for a 45°Wedge

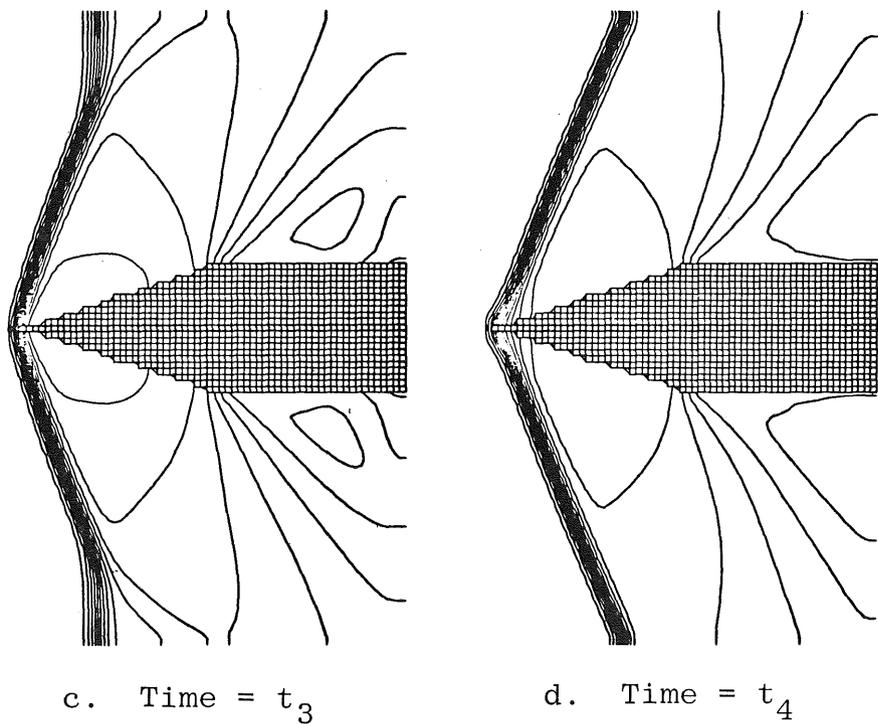
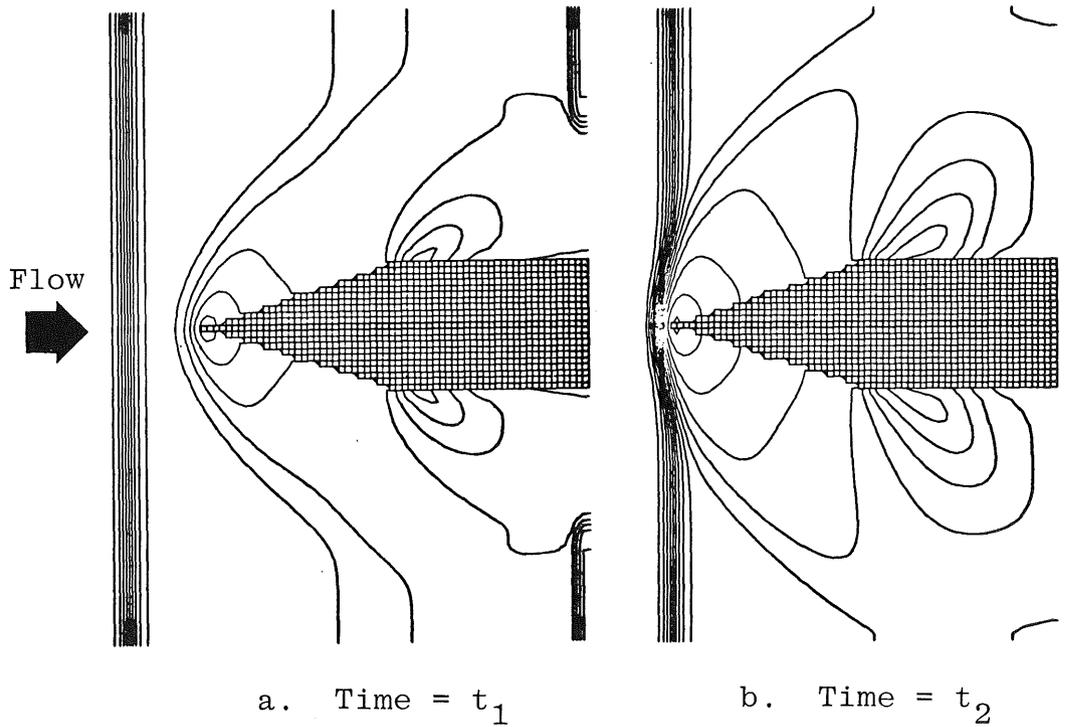
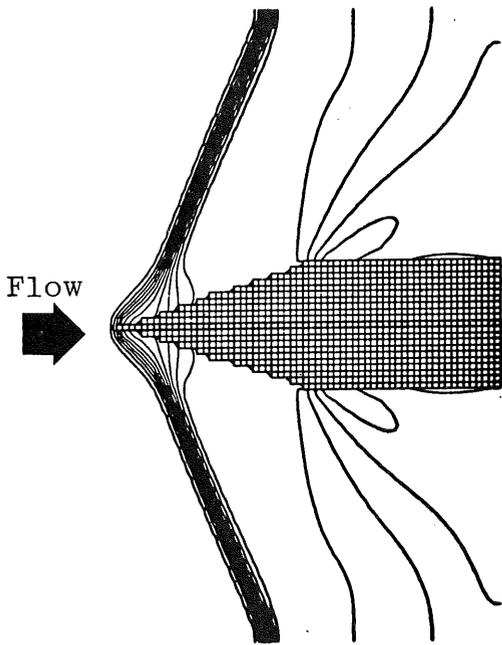
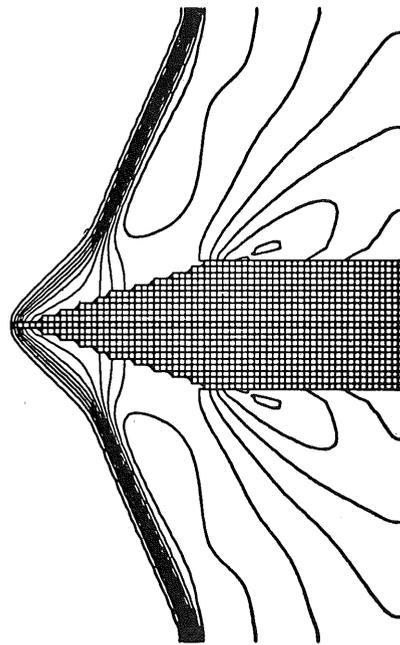


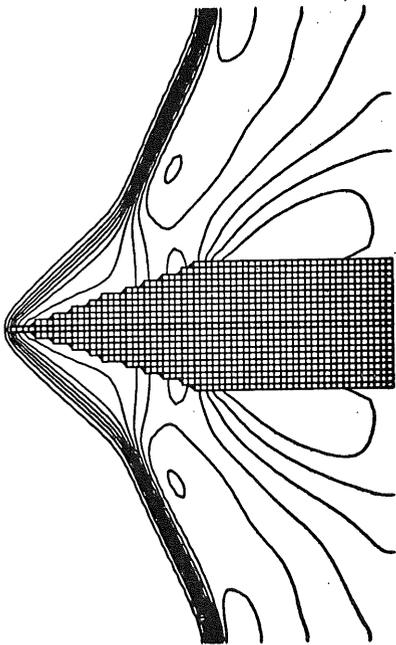
Fig. 14 Transient Shock Formation



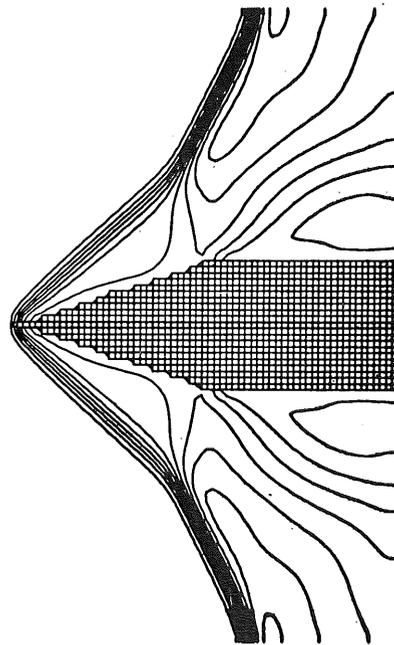
e. Time = t_5



f. Time = t_6

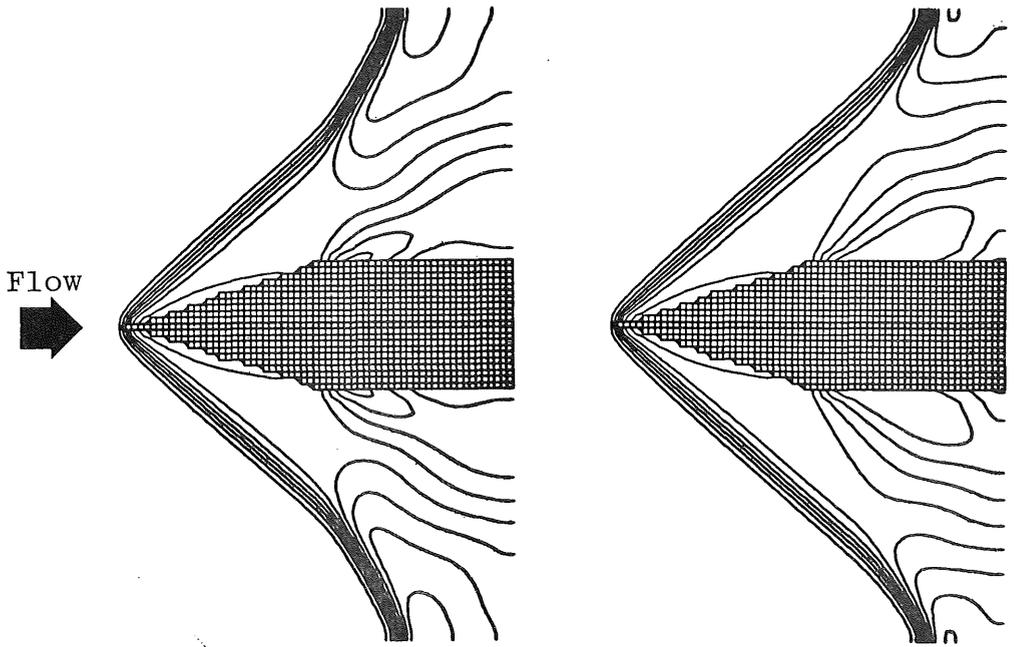


g. Time = t_7



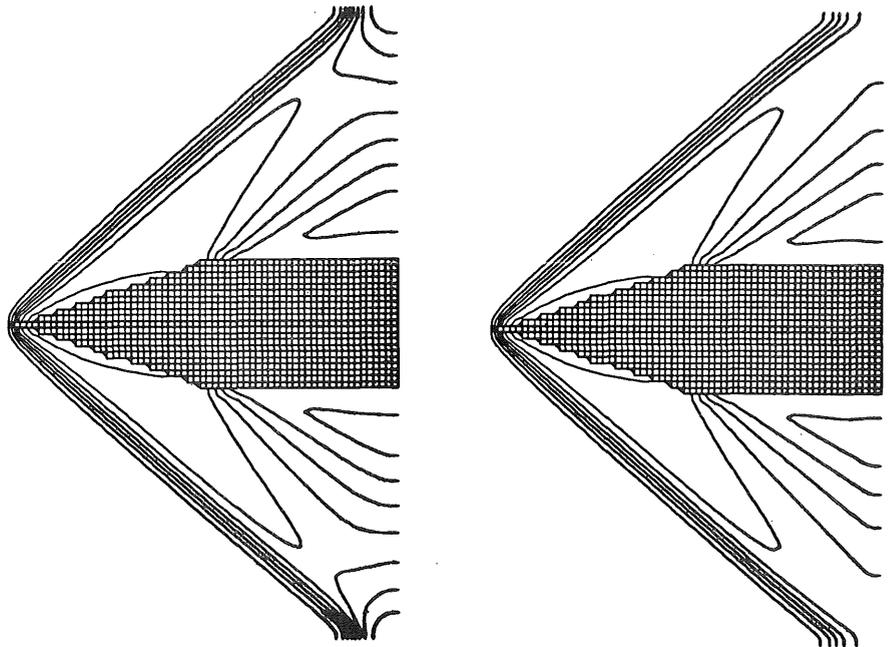
h. Time = t_8

Fig. 14 (Continued)



i. Time = t_9

j. Time = t_{10}



k. Time = t_{11}

l. Time = t_{12}

Fig. 14 (Continued)

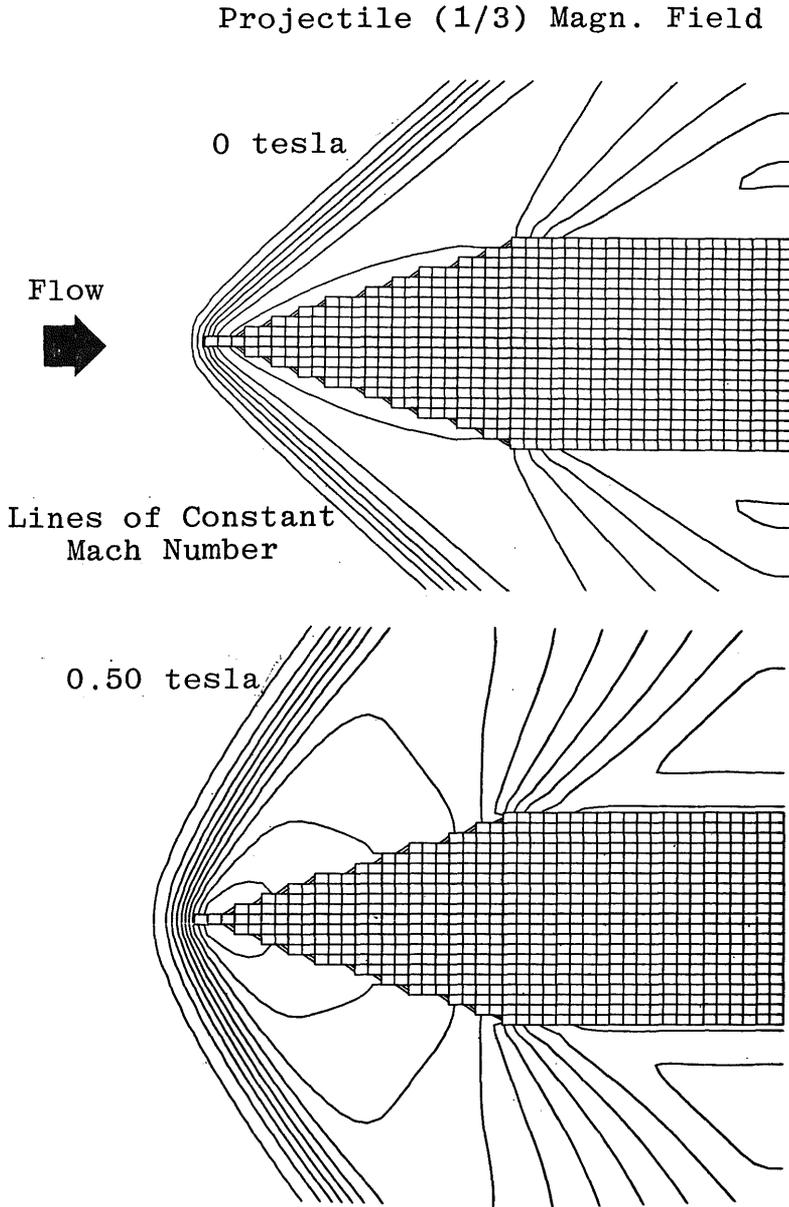


Fig. 15 Shock Detachment Induced by a Transverse Magnetic Field

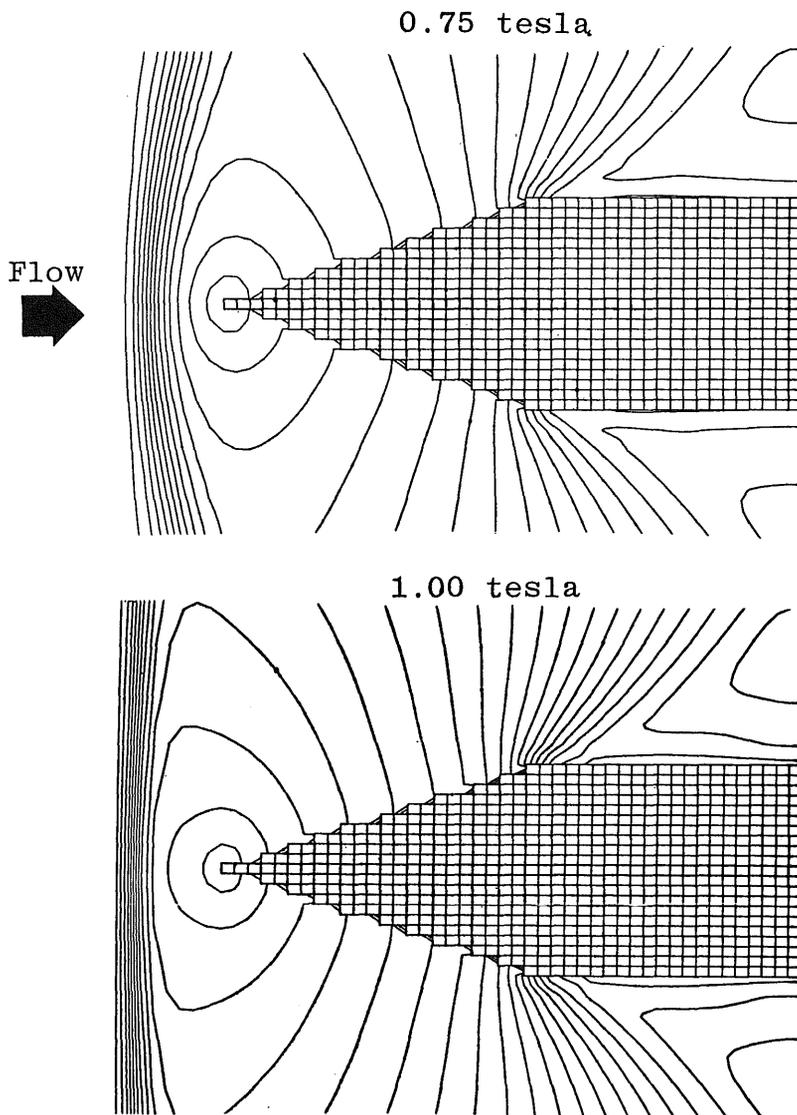


Fig. 15 (Continued)

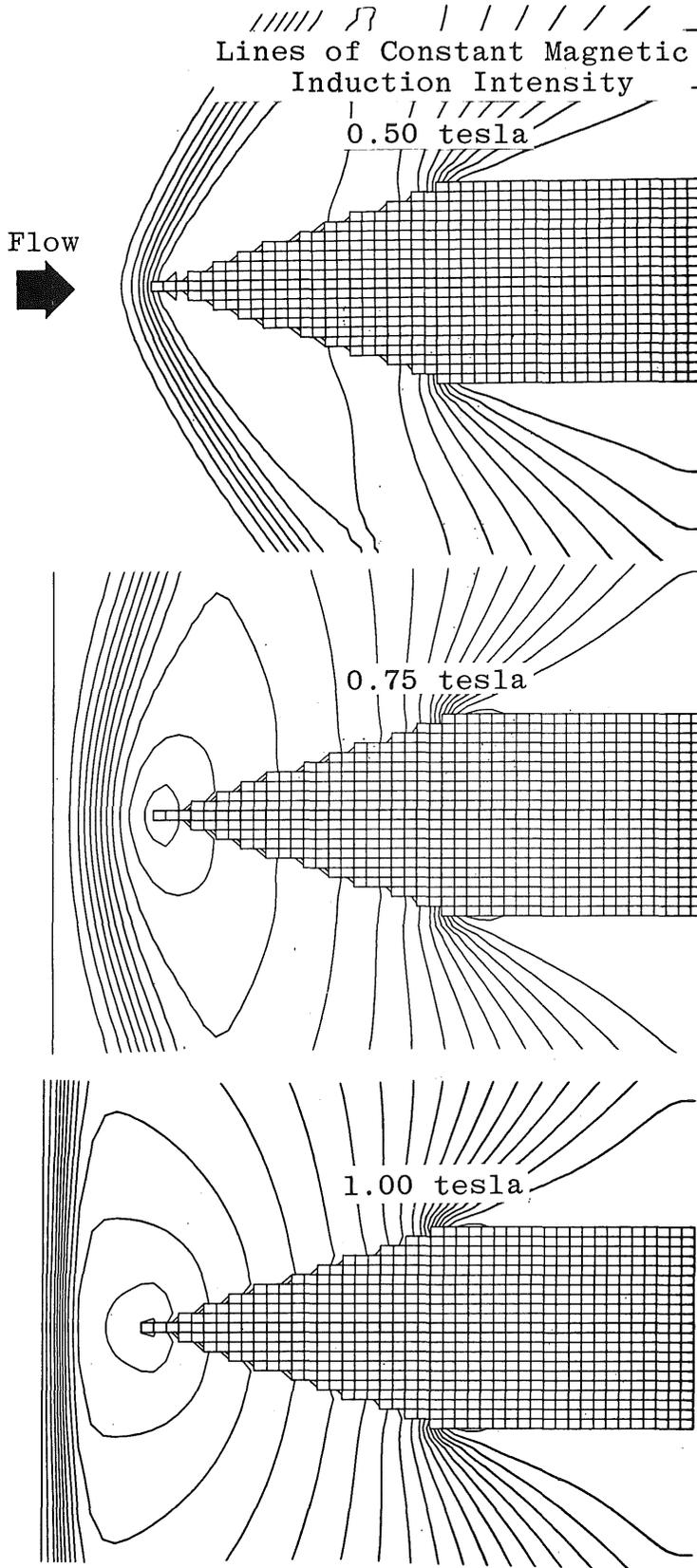


Fig. 15 (Continued)

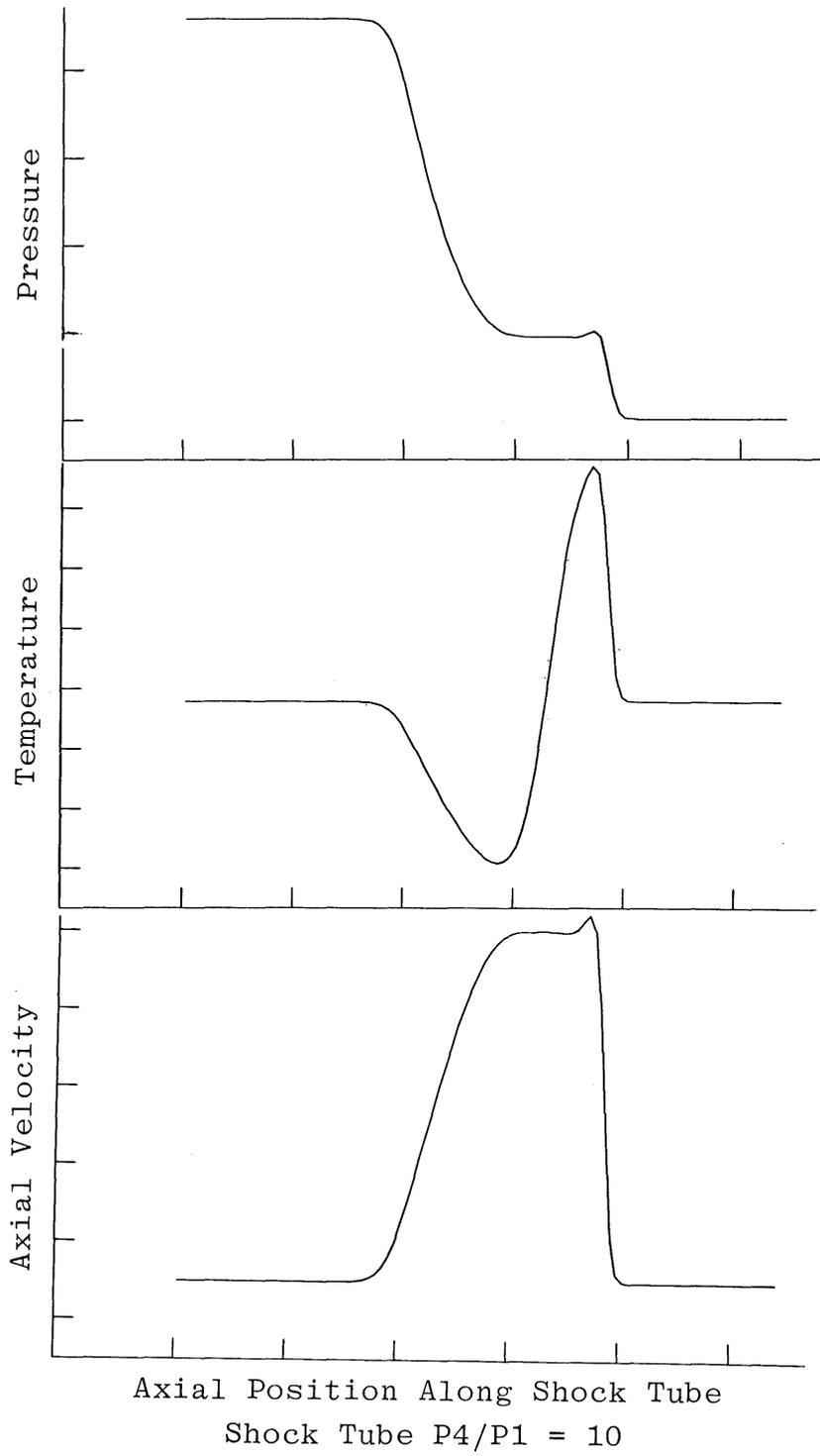


Fig. 16 Shock Tube Results

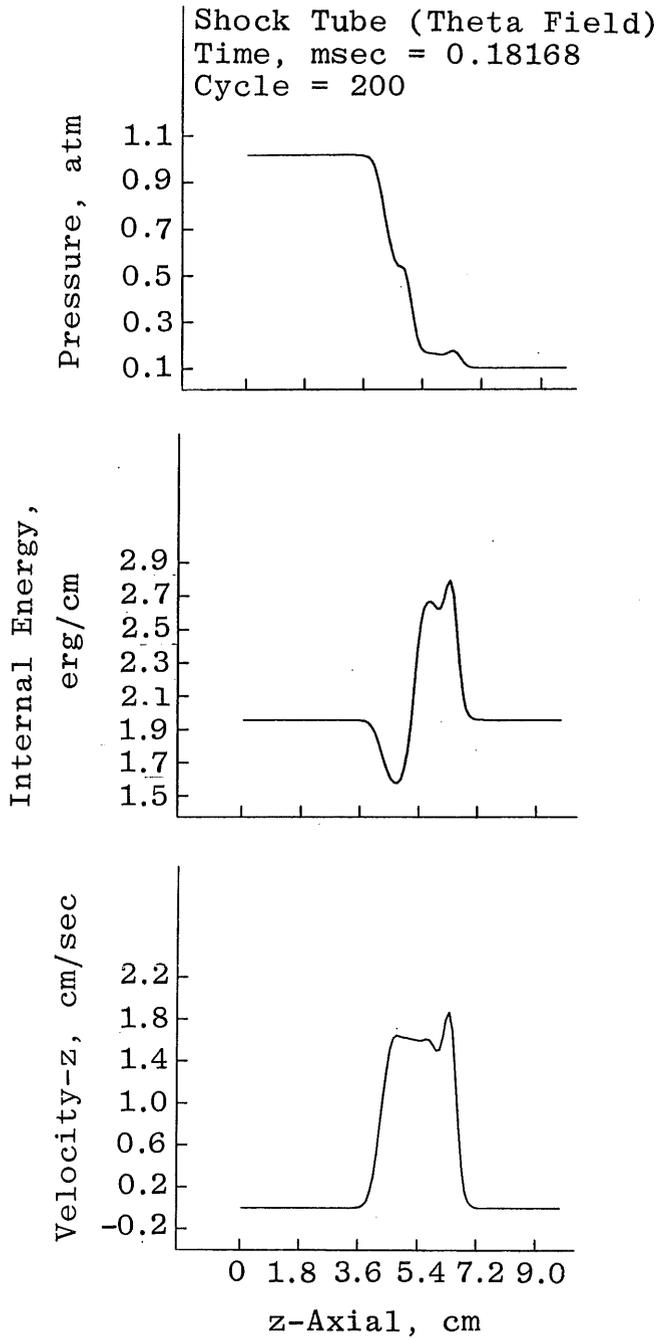


Fig. 16 (Continued)

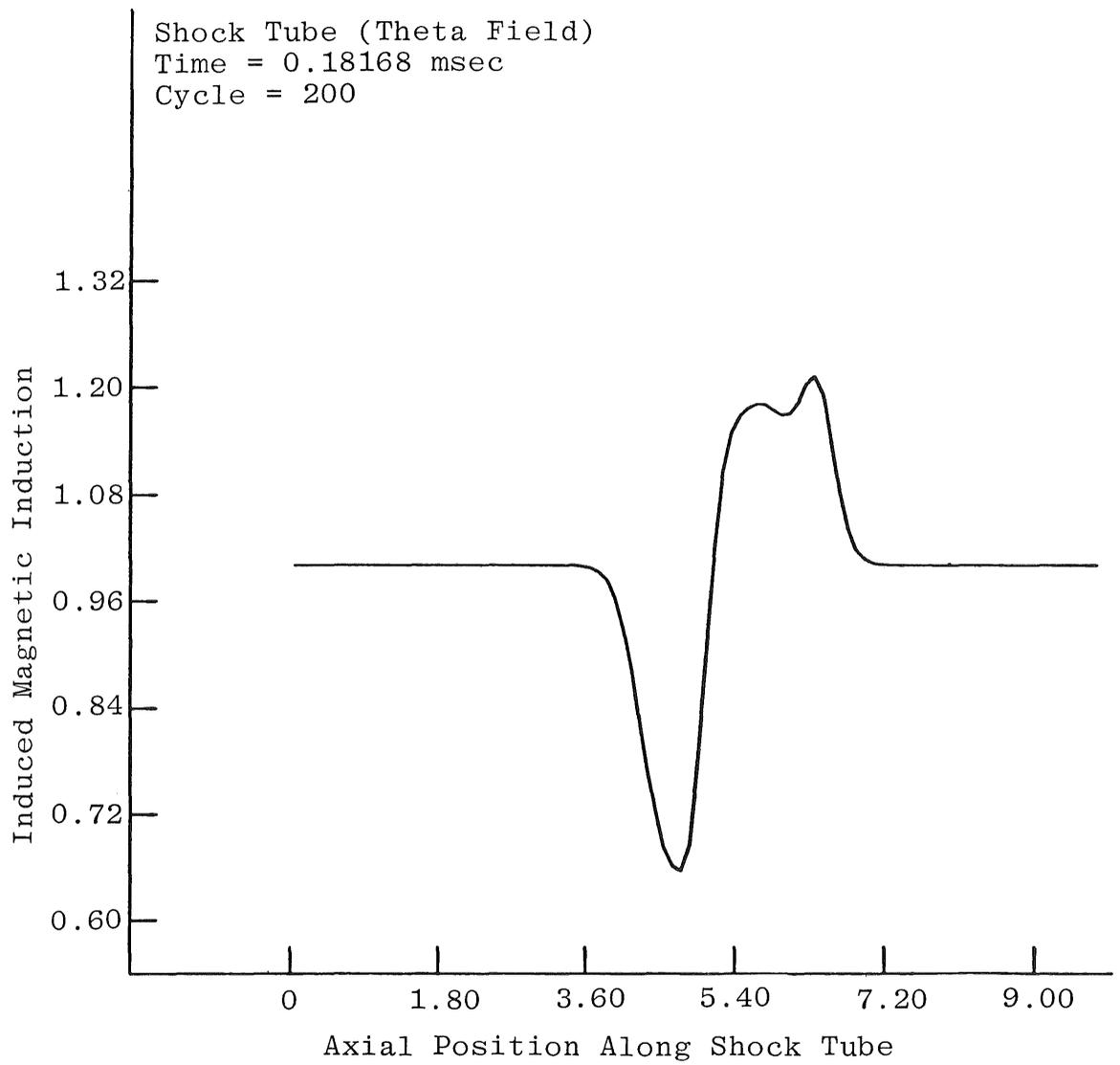


Fig. 16 (Continued)

$$C_s = a_1 \left(\frac{(\gamma-1)}{2\gamma} + \frac{(\gamma+1)}{2\gamma} \frac{p_2}{p_1} \right)^{1/2} \tag{171}$$

$$\frac{p_4}{p_1} = \frac{p_2}{p_1} \left[1 - \frac{(\gamma-1)(a_1/a_4)(p_2/p_1-1)}{\text{SQRT}\{(2\gamma)(2\gamma+(\gamma+1)(p_2/p_1-1))\}} \right]^{\frac{-2\gamma}{\gamma-1}} \tag{172}$$

ratio $(p_4/p_1) = 10$ and temperature ratio $(T_4/T_1) = 1$, will generate a shock moving into the lower pressure region at a speed of 52,800 cm/sec and produce a particle velocity = 28,400 cm/sec (p_2/p_1 is 2.86). Numerical results indicate a shock speed of approximately 53,600 cm/sec and pressure ratio of 2.98. A temperature and density ratio across the shock was numerically found to be 1.40 and 2.13, which compares favorably with 1.405 and 2.07, respectively, as predicted by theory.

Computing upstream and downstream Mach numbers relative to the moving shock:

$$M_x = C_s / c_2 = 53,600 / 33,000 = 1.625$$

where $c = (\gamma P / \rho)^{1/2}$

$$M_y = (C_s - U_p) / c_1 = (53,600 - 28,400) / 39,000 = 0.66$$

Table (1) compares the computed values of ρ_2/ρ_1 , p_2/p_1 , T_2/T_1 , M_2/M_1 , U_p and C_s with one-dimensional normal shock relations or the Rankine-Hugoniot equations and shows close agreement in all cases.

Table (1) Comparison of Results for $M_x = 1.625$

	Numerical Calculation	Rankine-Hugoniot Relations
M_x	1.625	1.625 (GIVEN)
M_y	0.665	0.66
p_2/p_1	2.98	2.92
ρ_2/ρ_1	2.13	2.07
T_2/T_1	1.40	1.405

Modifying the shock equations so as to introduce magnetic fields, the following equations result:

MHD Shock Relations in a Moving Coordinate System

$$\rho_1 u = \rho_2 (u - u_2) \quad (173)$$

$$p_1 + \frac{B_1^2}{2\mu_p} + \rho_1 u^2 = p_2 + \frac{B_2^2}{2\mu_p} + \rho_2 (u - u_2)^2 \quad (174)$$

$$\rho_1 u \left[\frac{\gamma}{\gamma - 1} \frac{p_1}{\rho_1} + \frac{B_1^2}{\rho_1 \mu_p} + \frac{u^2}{2} \right] = \rho_2 (u - u_2) \left[\frac{\gamma}{\gamma - 1} \frac{p_2}{\rho_2} + \frac{B_2^2}{\rho_2 \mu_p} + \frac{1}{2} (u - u_2)^2 \right] \quad (175)$$

u = shock speed

u_2 = particle velocity

B = magnetic induction

P = pressure

μ_p = magnetic permeability

ρ = density

C_s = shock velocity

γ = specific heat ratio

For an applied magnetic field strength of 1 Tesla, the values of pressure, temperature and velocity are modified as shown in Figure (16b) and (16c). Preservation of the Rankine-Hugoniot equations which indicates conservation of mass, momentum and energy through a normal shock was maintained.

Regular-Irregular Shock Reflection

Regular-irregular shock reflection has been studied most recently by numerous authors (90, 91, 92 and 93). Theory governing the transition from regular reflection (the formation of a reflected oblique

shock from an incident oblique shock) to irregular reflection (the formation of two oblique shocks and a normal shock) has been established. The principal objective in performing this calculation was to determine the program's effectiveness in computing a stable Mach stem or triple point. No attempt was made to study the extremely difficult and (computer) time consuming problems of repetitive triple point formation, especially those emanating from an under-expanded or over-expanded nozzle. Figures (17), (18), (19) and (20) illustrate the formation of this Mach stem. In Figure (17), velocity vectors depict the shock pattern. In Figures (18) and (19), pressure and Mach intensities are shown. Pressure contours are displayed in Figure (20) and finally the normal shock of the Mach stem is plotted in Figure (21). A triple point was also computed from flow exhausting from a nozzle as shown in Figure (22).

Other calculations include a detached bow shock over a semi-infinite cylinder as displayed in Figure (23), and a re-entry vehicle with a configuration (point of inflection) causing an imbedded shock (Figure (24)).

3.2 Boundary Layer

The most fundamental boundary layer problems investigated are (1) Couette flow, (2) viscous flow over a flat plate, (3) Rayleigh flow discussed in Section (3.4), and (4) turbulence.

Couette flow consists of flow in a parallel-wall channel where one wall is stationary and the other is moving. Two problems are examined: (1) the fluid is non-conducting and experiences only pressure and viscous forces and (2) the fluid is conducting and experiences pressure,

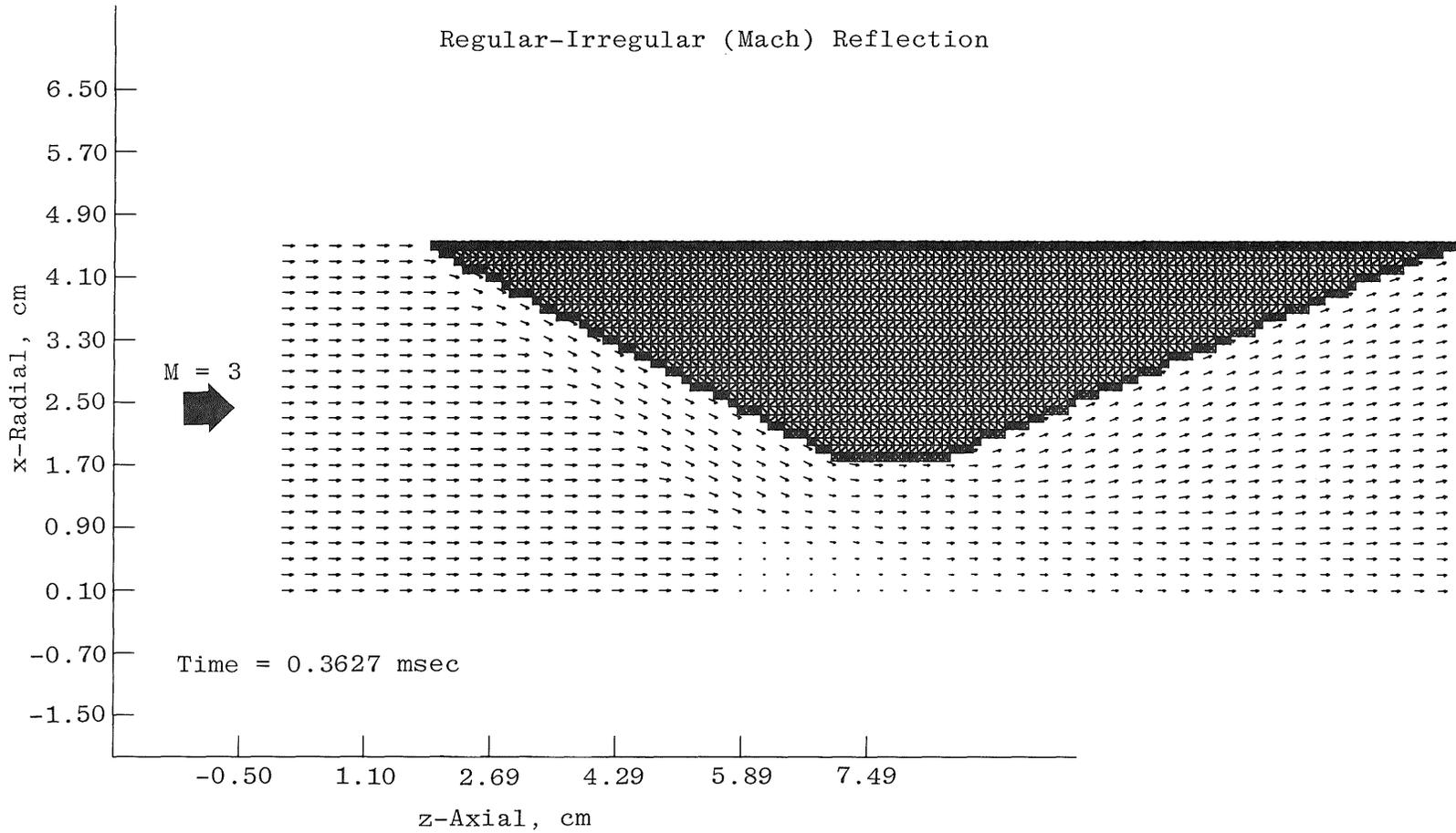


Fig. 17 Velocity Vectors of Irregular (Mach) Reflection

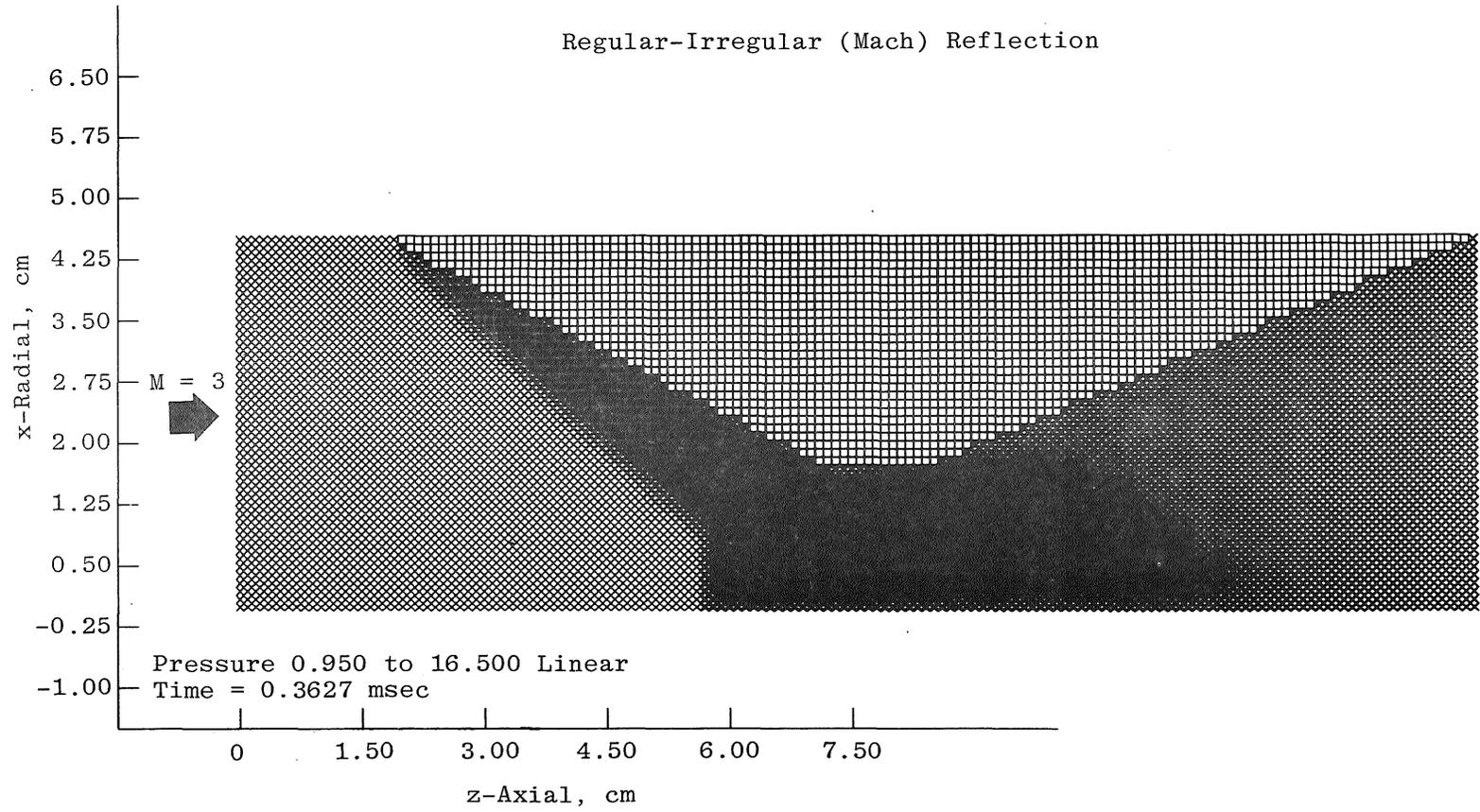


Fig. 18 Pressure Intensity (Shade) of Mach Stem

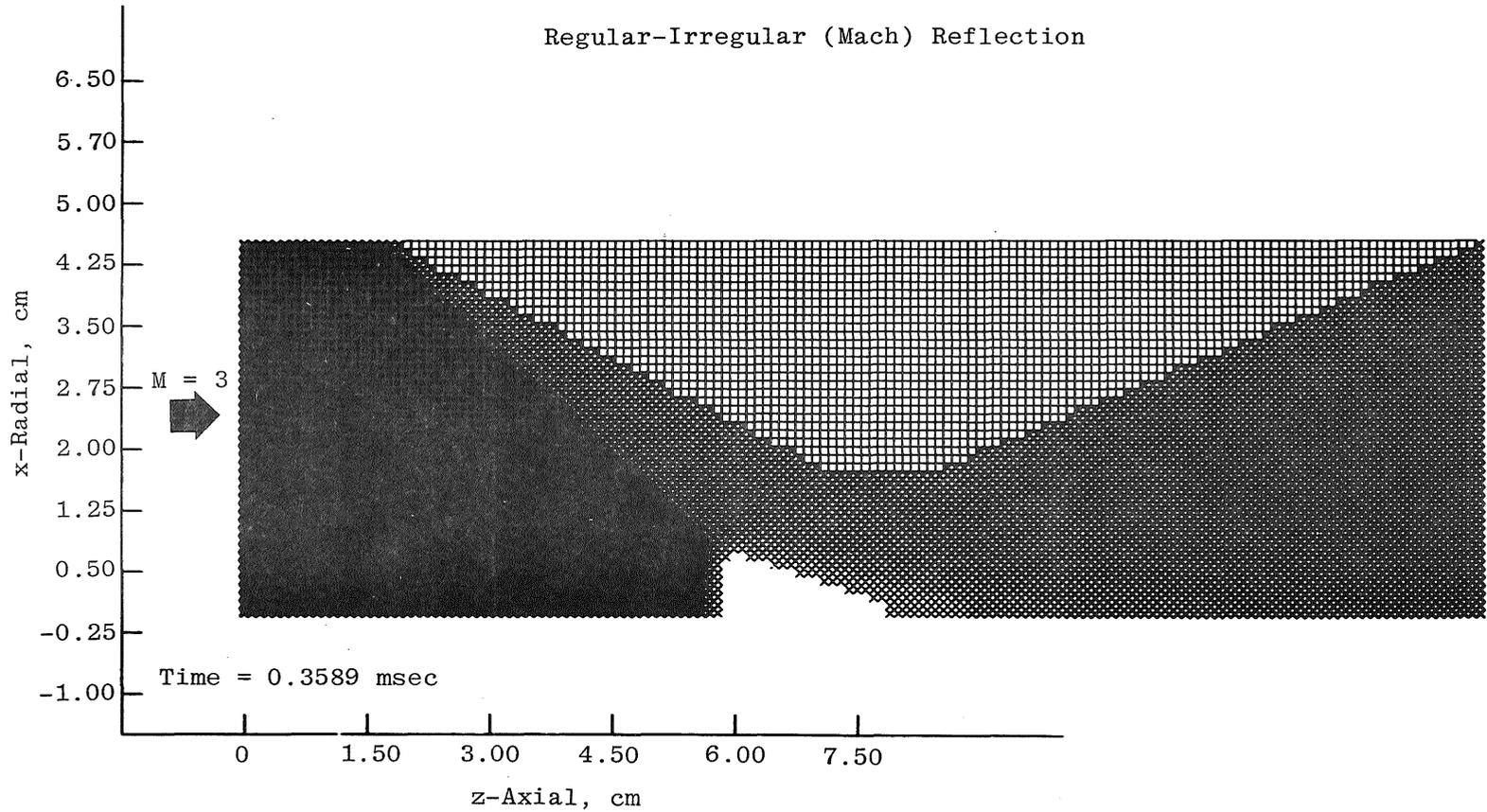


Fig. 19 Mach Number Intensity (Shade) of Mach Stem

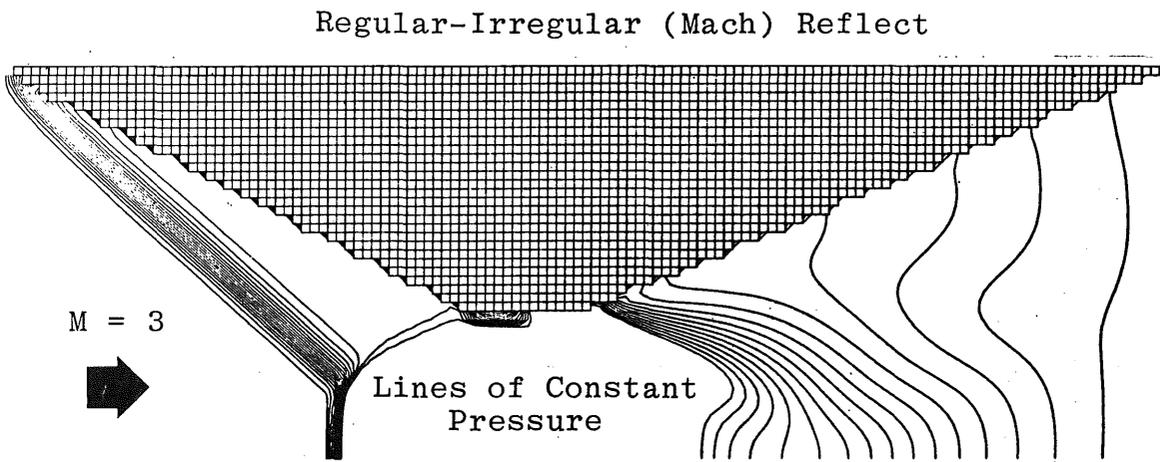


Fig. 20 Pressure Contours of Mach Stem

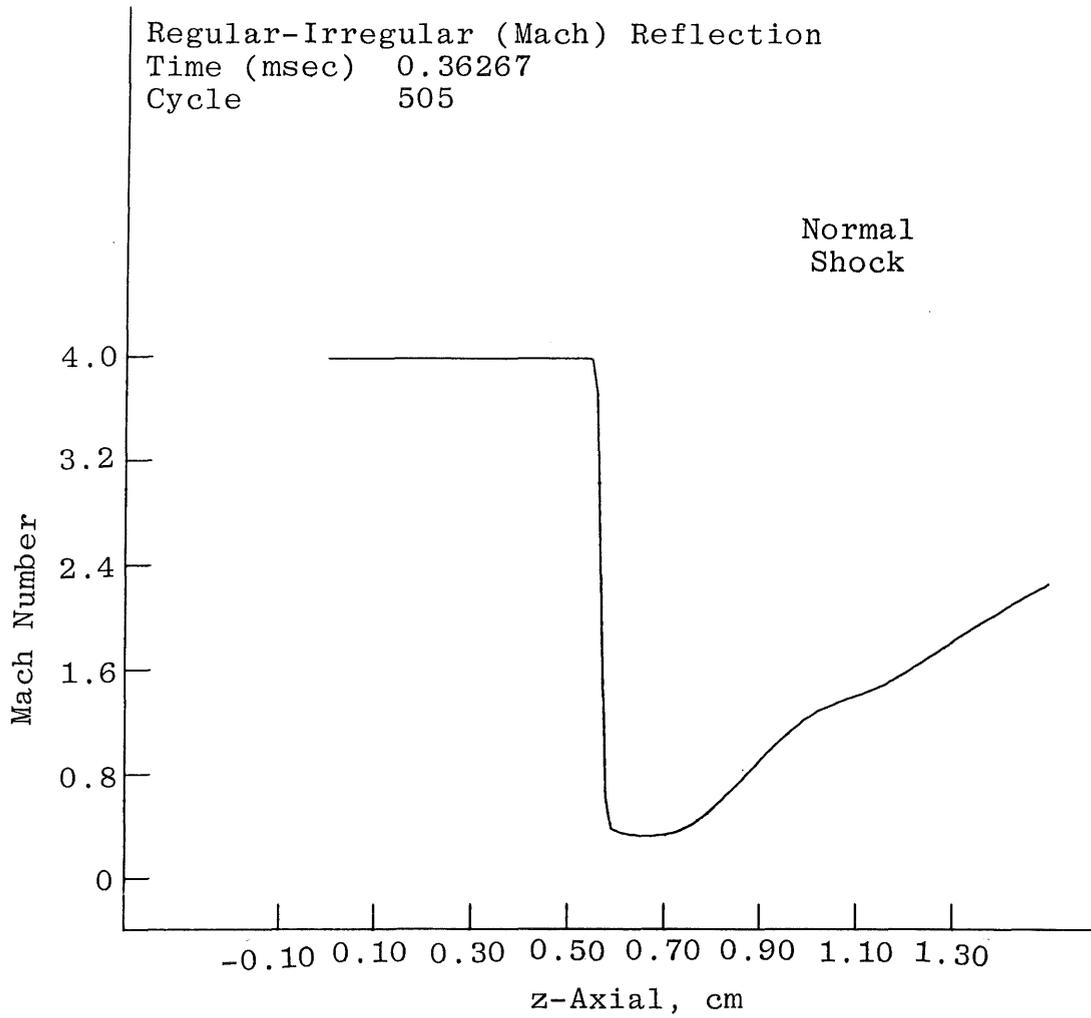


Fig. 21 Normal Shock of Mach Stem

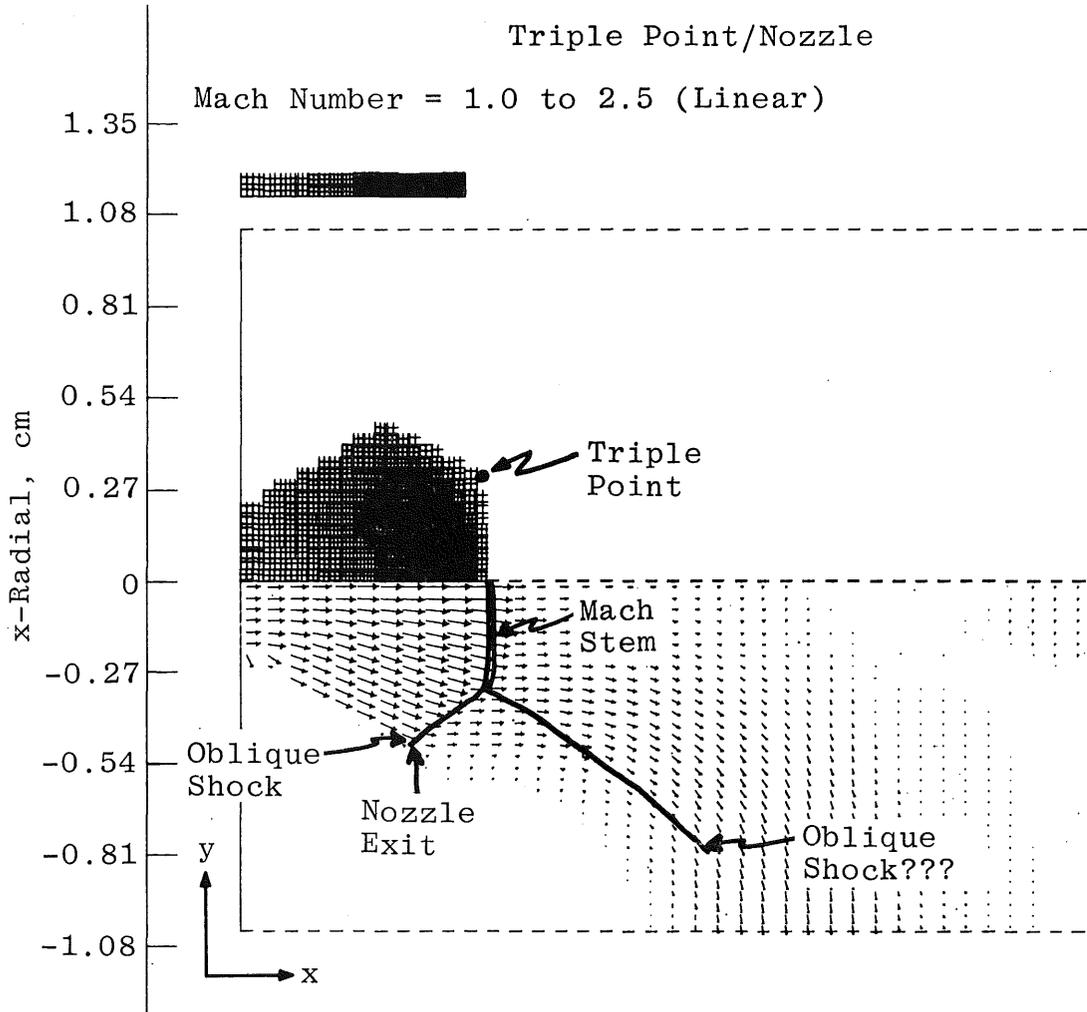


Fig. 22 Triple Point Emanating from a Nozzle

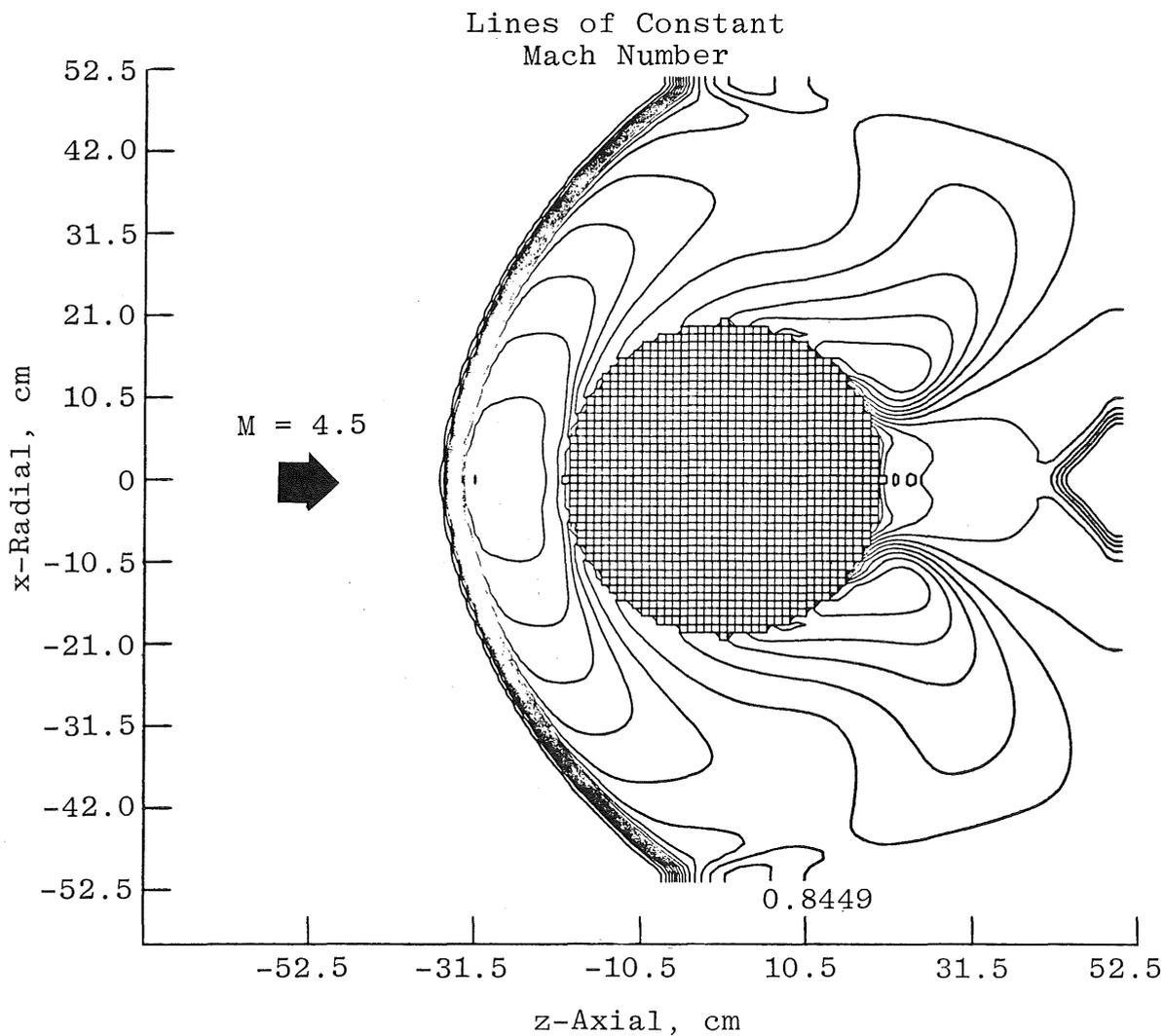


Fig. 23 Bow Shock over a Semi-Infinite Cylinder

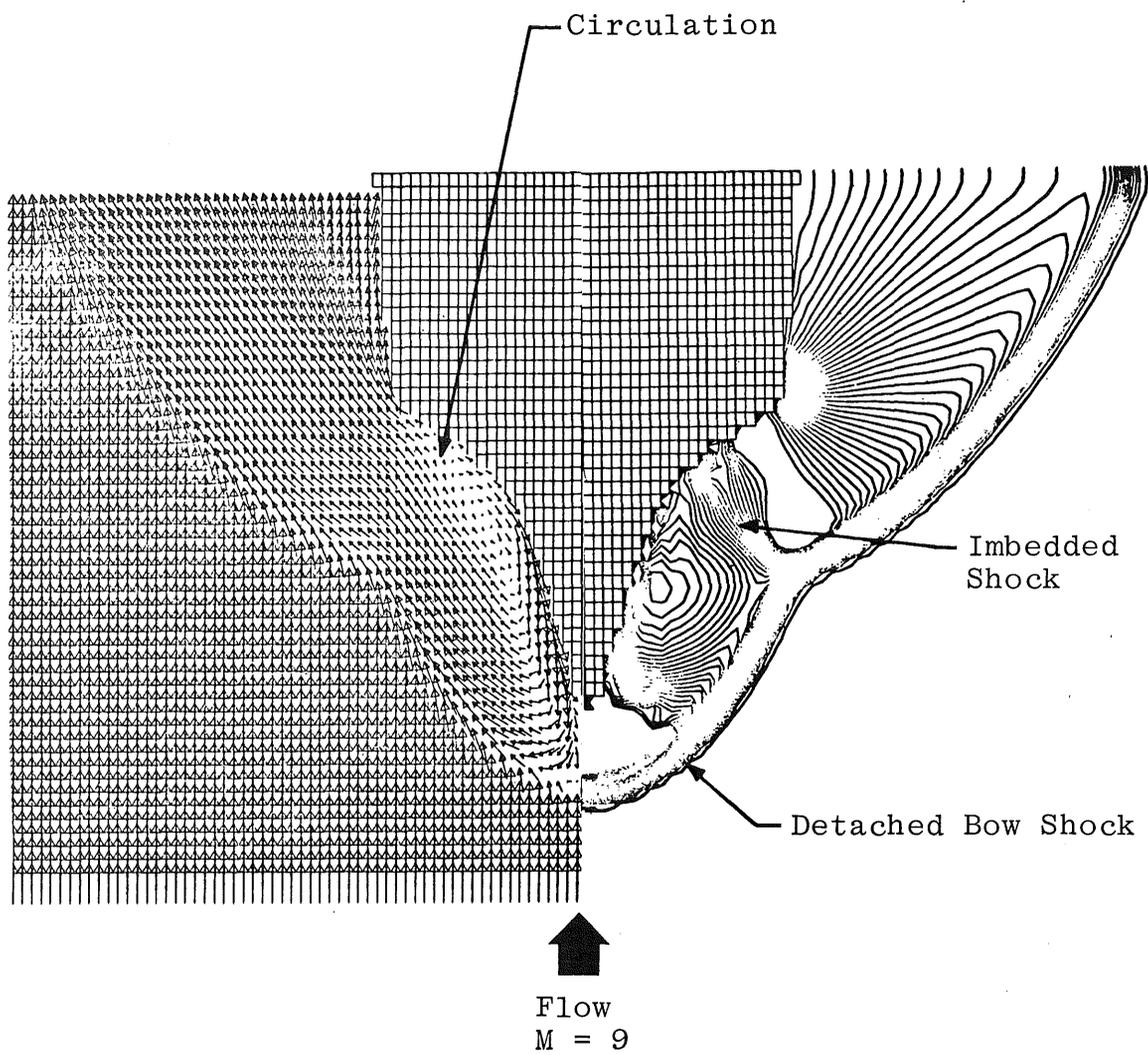


Fig. 24 Interacting Shocks off a Re-Entry Vehicle

viscous and Lorentz forces when under the influence of an applied magnetic field.

Couette Flow

Considering a non-conducting incompressible fluid, the equation of motion in the x-direction reduces to:

$$\rho \frac{\delta}{\delta t}(u) = -\frac{\delta}{\delta z}(p) + \mu \frac{\delta}{\delta r} \left(\frac{\delta}{\delta r}(u) \right) \quad (176)$$

At steady state, Equation (176) becomes:

$$\frac{\delta}{\delta z}(p) = \mu \frac{\delta}{\delta r} \left(\frac{\delta}{\delta r}(u) \right) \quad (177)$$

Applying the following boundary conditions:

$$u = 0, r = 0; u = U, r = \infty$$

a solution of the form

$$u = \frac{r}{h} \left[1 - \left(1 - \frac{r}{h} \right) P \right] \quad (178)$$

is obtained, where:

$$P = \frac{h^2}{2\mu U} \left(-\frac{\delta}{\delta z}(p) \right) \quad (179)$$

The cases for $P = -3, -2, -1$ (backflow), 0 (constant pressure), $+1, +2$ and $+3$ were run with results in close agreement with Schlichting (94). A disparity of approximately 10% was caused by a coarse mesh (ten cells) and a slightly varying time-dependent solution (Figure (25)).

Next, considering the transient Couette problem (Stokes' First Problem) at a constant pressure, and applying the same initial and boundary conditions as before, the transient solution is developed. Results are shown in Figure (25) with good comparison to the data presented in Schlichting (94).

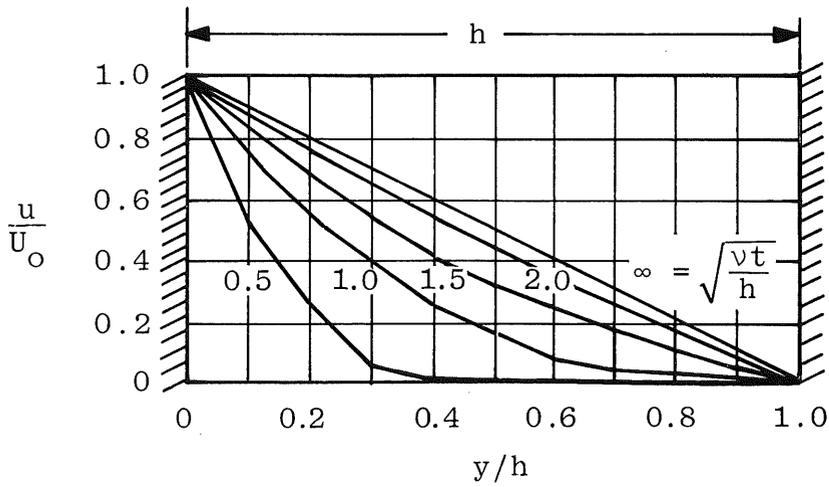
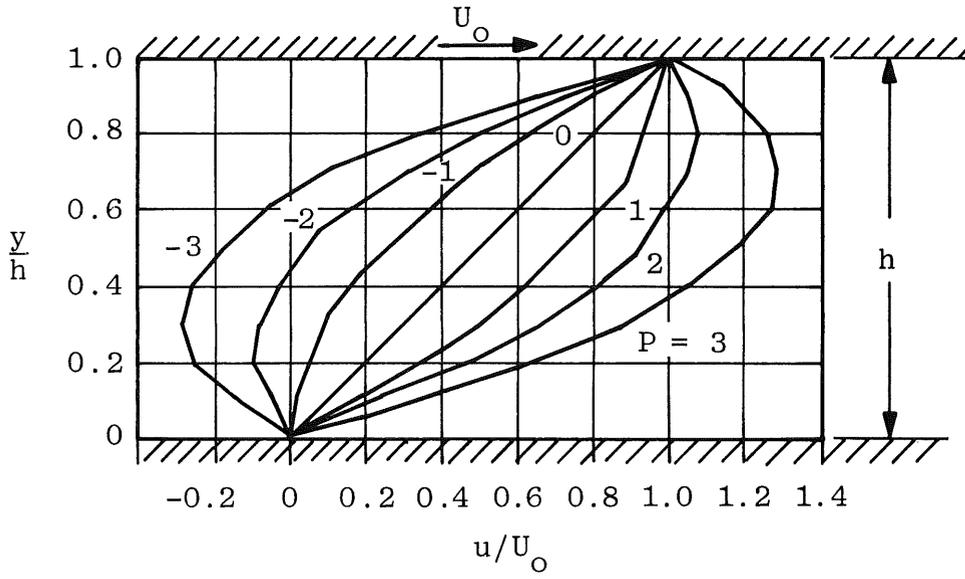


Fig. 25 Couette Flow. Transient and Steady State

Couette Flow - Thermal Distribution

The temperature distribution in Couette flow is governed by the energy equation and reduces to:

$$0 = -\lambda \frac{\delta}{\delta t} \left(\frac{\delta}{\delta t} (T) \right) + \mu \left\{ \frac{\delta}{\delta t} (u) \right\} \left\{ \frac{\delta}{\delta t} (u) \right\} \quad (180)$$

for the 1-D, steady case with constant thermal conductivity and viscosity. If both walls are maintained at constant temperature T_w then the solution of Equation (180) is parabolic and its analytic solution is shown in Table (2) along with numerical results.

Table (2) Thermal Distribution in Couette Flow

X/L	T/T_w	T/T_w
	Analytic	Numerical
0.	1.0000	1.0000
0.1	1.3600	1.3600
0.2	1.6400	1.6397
0.3	1.8400	1.8394
0.4	1.9600	1.9590
0.5	2.0000	1.9988
0.6	1.9600	1.9587
0.7	1.8400	1.8388
0.8	1.6400	1.6391
0.9	1.3600	1.3595
1.0	1.0000	1.0000

Couette - MHD Flow

The equation of motion in the axial direction (neglecting radial momentum) is given by:

$$\frac{\delta}{\delta t} (u) + u \frac{\delta}{\delta z} (u) + v \frac{\delta}{\delta r} (u) = -\frac{1}{\rho} \frac{\delta}{\delta z} (p) + \frac{1}{\rho} \frac{\delta}{\delta r} \left(\mu \frac{\delta}{\delta r} (u) \right) + \frac{1}{\rho} \bar{j} \times \bar{B} \quad (181)$$

Employing Ohm's Law, the Lorentz force $\bar{j} \times \bar{B}$ is replaced by

$$\bar{j} \times \bar{B} = \frac{\nabla \times \bar{B}}{\mu} \times \bar{k} = \frac{1}{\mu} \frac{\delta}{\delta r} (B_z \bar{B}) \quad (182)$$

where \bar{k} is the unit normal vector

where B_z is the induced magnetic field and B is the applied magnetic field. Also, from the magnetic induction equation

$$\frac{\delta}{\delta t}(\bar{B}_z) = -\frac{\nabla_x \nabla_x B_z \bar{k}}{\mu \sigma} + \nabla_x \bar{v} \times B_z \bar{k} \quad (183)$$

at steady state, this equation reduces to:

$$\frac{1}{\sigma \mu} \frac{\delta}{\delta r} \left(\frac{\delta}{\delta r} (B_z) \right) = \frac{\delta}{\delta r} (u B_z) \quad (184)$$

and upon integration yields:

$$\frac{1}{\mu} \frac{\delta}{\delta r} (B) B_z = \sigma u B_z^2 \quad (185)$$

The Lorentz force then becomes $u B_z^2$ and the equation of motion at steady state (constant viscosity) reduces to:

$$\frac{\mu}{\rho} \frac{\delta}{\delta r} \left(\frac{\delta}{\delta r} (u) \right) = \frac{\delta}{\delta r} (p) + \sigma u B_z^2 \quad (186)$$

with boundary conditions:

$$u = u(r = 0), \quad u = 0 \quad (r = h)$$

Non-dimensionalizing u and r to the free stream velocity and channel width, respectively, the solution to Equation (186), neglecting the pressure gradient, is

$$u = \frac{\text{SINH}(H_a Y)}{\text{SINH}(H_a)} \quad (187)$$

$$B_z = \frac{\text{COSH}(H_a) - \text{COSH}(H_a Y)}{\text{SINH}(H_a)} \quad (188)$$

where H_a is the Hartmann number

$$H_a^2 = \frac{\sigma B_o^2 h^2 \rho}{\mu} \quad (189)$$

U is the non-dimensional velocity and Y is the non-dimensional width.

As H_a goes to zero

$$u = \frac{H_a Y}{H_a} = Y \quad (190)$$

If B_z also vanishes the solution for couette flow results.

Comparison of numerical and analytic results are shown in Table (3) with good agreement in all cases.

Table (3) Couette Flow with a Transverse Magnetic Flow

y/h	<u>Analytic Solution</u>		<u>Numerical Solution</u> [†]	
	u/U_o	B^*	u/U_o	B^*
0.0	0.	0.240	0.	0.243
0.1	0.02	0.240	0.025	0.243
0.2	0.05	0.238	0.051	0.241
0.3	0.08	0.234	0.081	0.238
0.4	0.12	0.230	0.118	0.230
0.5	0.18	0.220	0.166	0.219
0.6	0.22	0.200	0.234	0.205
0.7	0.30	0.170	0.330	0.178
0.8	0.44	0.120	0.472	0.142
0.9	0.69	0.070	0.683	0.086
1.0	1.00	0.	1.00	0.

$B^* \equiv$ normalized induced magnetic field

[†] flow not exactly steady or incompressible

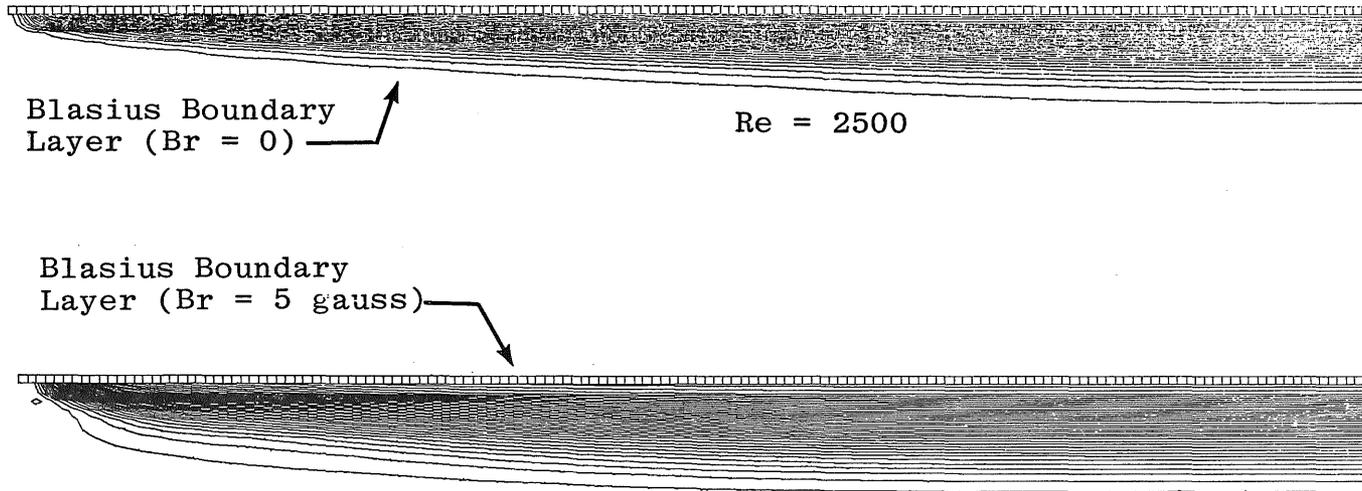
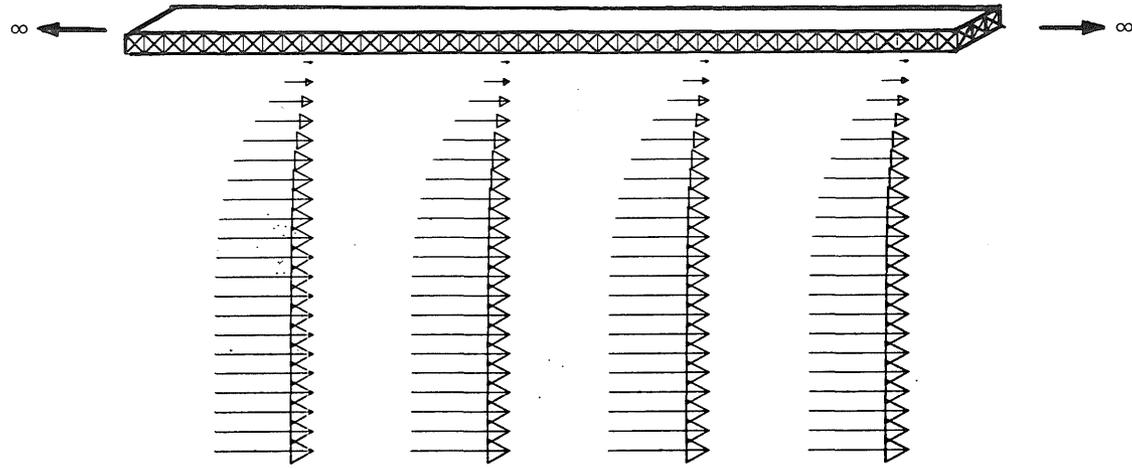
Flat Plate

The boundary layer along a flat plate (Figure (26)) is described by the following boundary layer equations and boundary conditions:

$$u \frac{\delta}{\delta z}(u) + v \frac{\delta}{\delta r}(u) = \frac{\mu}{\rho} \frac{\delta}{\delta r} \left(\frac{\delta}{\delta r}(u) \right) \quad (191)$$

$$\frac{\delta}{\delta z}(u) + \frac{\delta}{\delta r}(v) = 0 \quad (192)$$

$$r = 0, u = v = 0; r = \infty, u = u_{\infty} \quad (193)$$



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Fig. 26 Laminar Boundary Layer over a Flat Plate

Blasius developed a series solution to the transformed ordinary differential equation which replaced the partial differential equations described above.

Blasius predicted a boundary layer thickness δ equal to $5x/Re_x^{-1/2}$. In Figure (26) numerical results for the case where $\rho = 0.001 \text{ gm/cm}^3$, $\mu = 0.0001 \text{ cp}$, $u = 833 \text{ cm/sec}$ are shown. The boundary layer thickness at $x = 0.048 \text{ cm}$ was found to be 0.011 cm which compares favorably with the Blasius prediction of 0.01 cm .

MHD Flow over a Flat Plate

Incompressible viscous flow over a flat plate in the presence of a transverse magnetic field was investigated by Rossow (33). The flow in the boundary layer is described by:

$$\rho(u \frac{\delta}{\delta z}(u) + v \frac{\delta}{\delta r}(u)) + \frac{\delta}{\delta z}(p) = -\sigma B_z^2 u + \frac{\delta}{\delta r}(u \frac{\delta}{\delta r}(u)) \quad (194)$$

and in the inviscid free stream:

$$\frac{\delta}{\delta z}(p) = -\sigma B_z^2 u \quad \frac{\delta}{\delta z}(u) = 0 \quad (195)$$

and with boundary conditions

$$u = 0, \quad y = 0; \quad u = u, \quad y = \pi.$$

Applying an external magnetic field to the previously discussed flat plate problem, and assuming now that the fluid is electrically conducting, the boundary layer becomes distorted as shown in Figure (26).

Turbulent Jet

The equations of motion applied to a turbulent problem are:

$$\frac{\delta}{\delta t}(u) + u \frac{\delta}{\delta z}(u) + v \frac{\delta}{\delta r}(u) = \frac{1}{\rho} \frac{\delta}{\delta r}(\tau) \quad (196)$$

$$\frac{\delta}{\delta z}(u) + \frac{\delta}{\delta r}(v) = 0 \quad (197)$$

Schlichting discusses the free turbulent jet flow problem (Figure (27)) and presents theoretical results of Gortler and measurements made by Reichardt. Employing a virtual kinematic viscosity based on the Prandtl hypothesis:

$$\varepsilon = \rho \lambda \frac{2\delta}{E\delta r} u = Ax(U_1 - U_2) \quad (198)$$

where U_1 and U_2 are velocities of two mixing streams.

The equations of motion for the steady case reduce to:

$$u \frac{\delta}{\delta z}(u) + v \frac{\delta}{\delta r}(u) = \varepsilon \frac{\delta}{\delta r} \left(\frac{\delta}{\delta r}(u) \right) \quad (199)$$

Solution of this equation by similarity transformation yields an equation identical to that of the Blasius equation for a flat plate, but with different boundary conditions. Based on measurements performed by Reichardt (A is evaluated) an eddy kinematic viscosity is computed from empirical data and excellent results between theory and experiment were obtained. The solution to the Blasius equation is the error function, and u was found to be:

$$u = \frac{(U_1 + U_2)}{2} \left\{ 1 + \frac{U_1 - U_2}{U_1 + U_2} \text{ERF}(\varepsilon) \right\}; \quad \varepsilon = \sigma \frac{r}{z} \quad (200)$$

This problem was solved numerically and results are compared with those of Gortler and Reichardt in Figures (28) and (29).

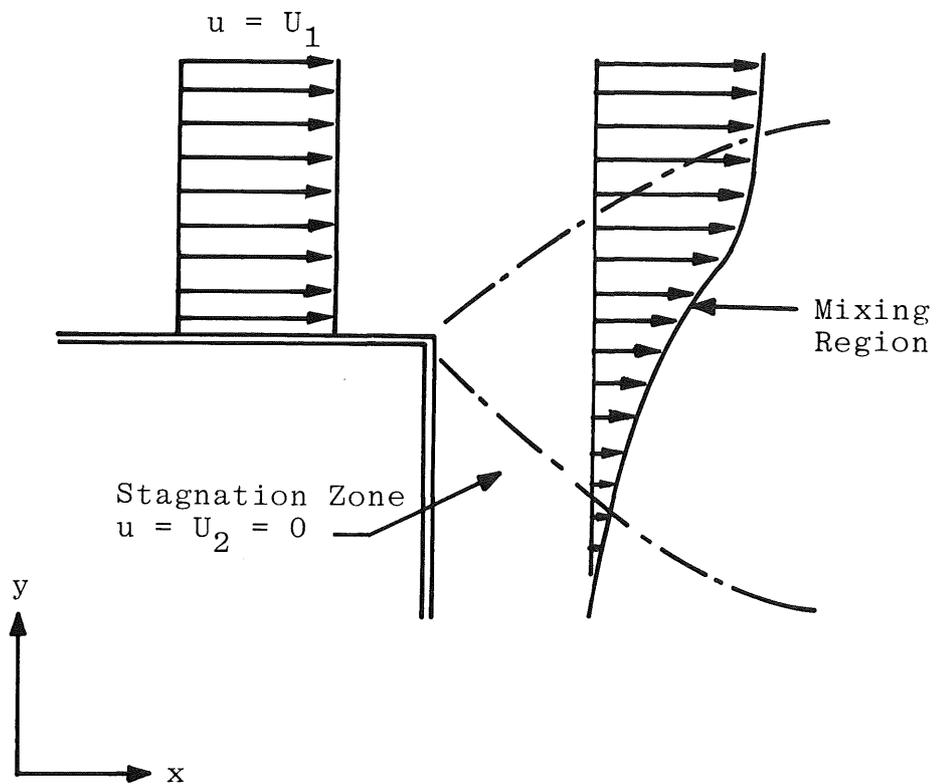


Fig. 27 Free Jet Turbulent Flow (Mixing Resulting Entirely from Turbulence, $p = 0$)

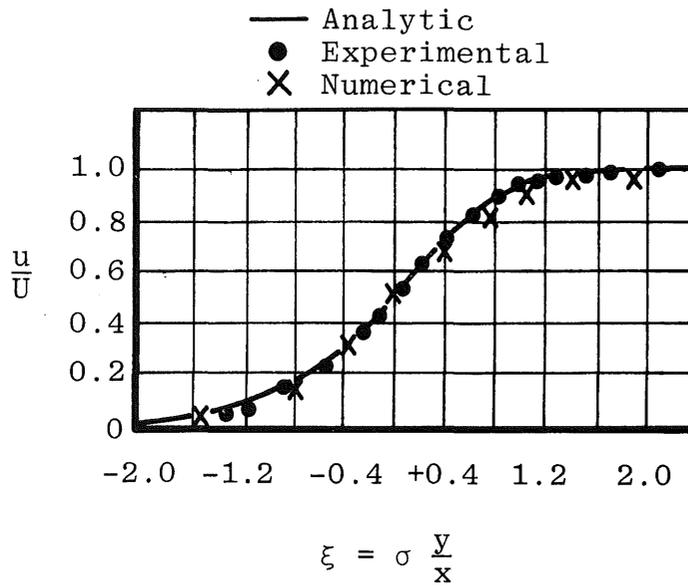


Fig. 28 Experimental and Numerical Data for Free Jet Turbulent Flow

Turbulent Jet

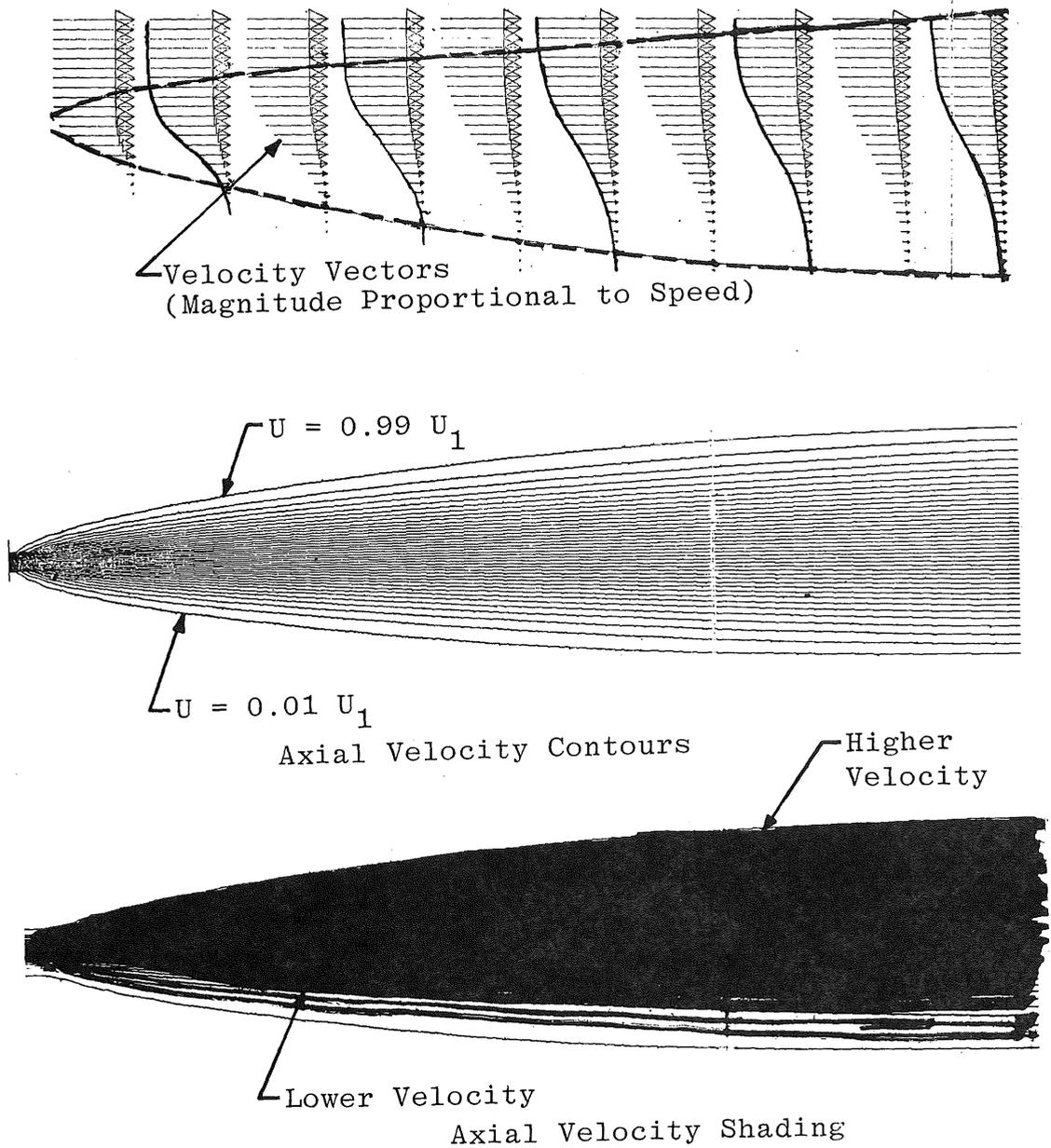


Fig. 29 Numerical Results for Free Jet Turbulent Flow

3.3 Compressible Flow

Compressible flow problems consisted of internal flow in a nozzle and external flow around an RV and M-117 warhead.

Nozzle Flow

Flow in a nozzle was investigated with attention focused on the phenomena of choking, shocks and flow separation.

Analytic solutions to certain one-dimensional gas dynamic problems are easily developed. For a perfect gas, isentropic flow and varying area, the conservation equations yield the following thermodynamic relations:

$$\frac{p_o}{p_x} = \left(1 + \frac{\gamma-1}{2} M_x^2\right)^{\gamma/(\gamma-1)} \quad (201)$$

$$\frac{\rho_o}{\rho_x} = \left(1 + \frac{\gamma-1}{2} M_x^2\right)^{1/(\gamma-1)} \quad (202)$$

$$\frac{T_o}{T_x} = \left(1 + \frac{\gamma-1}{2} M_x^2\right) \quad (203)$$

$$\frac{A_y}{A_x} = \frac{M_x}{M_y} \left(\frac{T_x}{T_y}\right)^{1/2} \quad (204)$$

where P, ρ, T, A and M denote pressure, density, temperature, area and Mach number, respectively, at chamber conditions (o) or stations (x) and (y).

Considering flow at constant area, the conservation equations become:

$$\rho_1 u_1 = \rho_2 u_2 \quad (205)$$

$$p_1 + \rho_1 u_1^2 = p_2 + \rho_2 u_2^2 \quad (206)$$

$$H_1 + \frac{u_1^2}{2} = H_2 + \frac{u_2^2}{2} \quad (207)$$

where H_1 and H_2 are the total enthalpy per unit mass. Equations (205) through (207) hold before and after the shock. Equations (205) and (207) are valid for Fanno Flow (friction), whereas Equations (205) and (206) are satisfied for Reyleigh flow (heat transfer).

For a normal shock these equations are rearranged to yield the Rankine-Hugoniot expressions:

$$\frac{p_2}{p_1} = 1 + \frac{2\gamma}{\gamma+1}(M_1^2 - 1) \quad (208)$$

$$\frac{\rho_2}{\rho_1} = \frac{u_1}{u_2} = \frac{(\gamma+1)M_1^2}{(\gamma-1)M_1^2 + 2} \quad (209)$$

$$\frac{p_{o_2}}{p_{o_1}} = \left[1 + \frac{2\gamma}{\gamma+1}(M_1^2 - 1) \right]^{1/(1-\gamma)} \left[\frac{(\gamma+1)M_1^2}{(\gamma-1)M_1^2 + 2} \right]^{\frac{\gamma}{\gamma-1}} \quad (210)$$

A fundamental problem of obvious considerable importance to the aerospace engineer is flow in a nozzle where the inviscid equations described above hold. Problems investigated in this section concern compressible, inviscid flow where choking, shocks and heat and pressure losses are experienced.

Nozzle flow was examined for choking; flow separation; stationary shocks; and 1-D influence of area change on pressure, density and

temperature. A 2-D calculation was performed with a chamber to ambient pressure ratio of 11.6. Table (4) compares the isentropic Mach number and the pressure, density and temperature ratios to the area ratio for both analytic (1-D) and numerical (2-D) results (see Figure (30)). Conditions at the throat were found to be $M = 1.$, $p/p_o = 0.45$, $T/T_o = 0.90$, $\rho/\rho_o = 0.5$ which agrees within 10-20% of the 1-D analytic solutions. The 2-D effects, although not severe, are significant enough to be considered in future calculations.

Table (4) Isentropic Conditions in the Nozzle

<u>Z</u> axial position	ρ	U	P	T	M
0.0	0.0150	0	11.59	117.2	0
0.2	0.0105	7515	8.04	116.6	0.228
0.4	0.0104	6411	8.25	120.1	0.191
0.6	0.0106	5352	8.58	122.9	0.159
0.8	0.0106	5110	8.68	124.6	0.150
1.0	0.0105	5465	8.67	124.9	0.169
1.2	0.0104	6227	8.65	125.7	0.182
1.4	0.0104	7335	8.64	125.9	0.214
1.6	0.0104	8783	8.61	126.0	0.256
1.8	0.0103	10619	8.54	126.0	0.310
2.0	0.0101	12934	8.40	125.8	0.377
2.2	0.00981	15846	8.11	125.3	0.463
2.4	0.00931	19523	7.62	124.1	0.573
2.6	0.00853	24190	6.85	121.8	0.717
2.8	0.00744	29261	5.78	117.4	0.882
<u>throat</u>					
3.0	0.00639	33854	4.75	112.9	1.041
3.2	0.00549	37800	3.91	108.1	1.188
3.4	0.00473	41254	3.24	103.8	1.324
3.6	0.00407	44414	2.67	99.6	1.455
3.8	0.00348	47371	2.19	95.5	1.585
4.0	0.00296	50139	1.78	91.5	1.715
4.2	0.00252	52709	1.46	87.6	1.841
4.4	0.00215	55071	1.19	84.1	1.964
4.6	0.00185	57215	0.985	80.9	2.079
4.8	0.00161	58896	0.8333	78.45	2.175

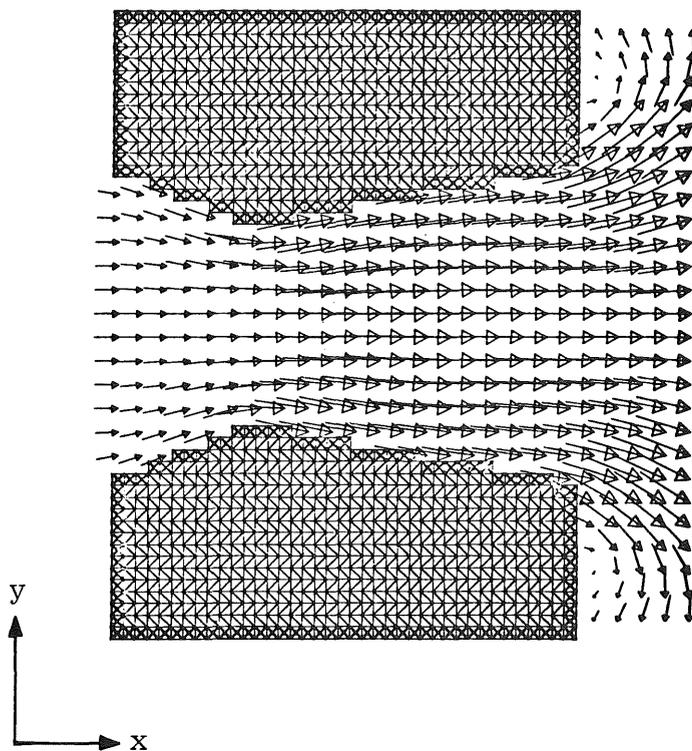
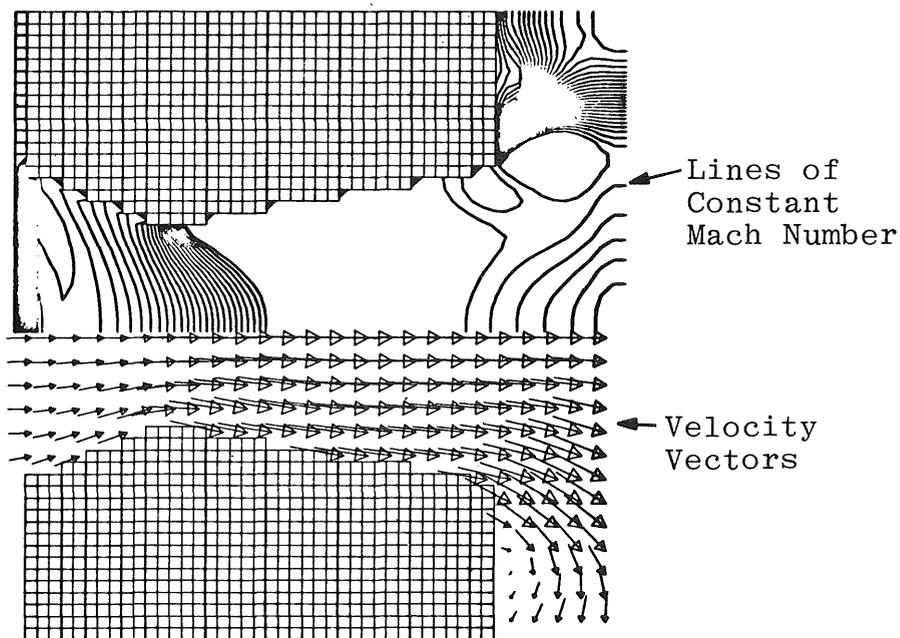


Figure 30 Isentropic Nozzle Flow

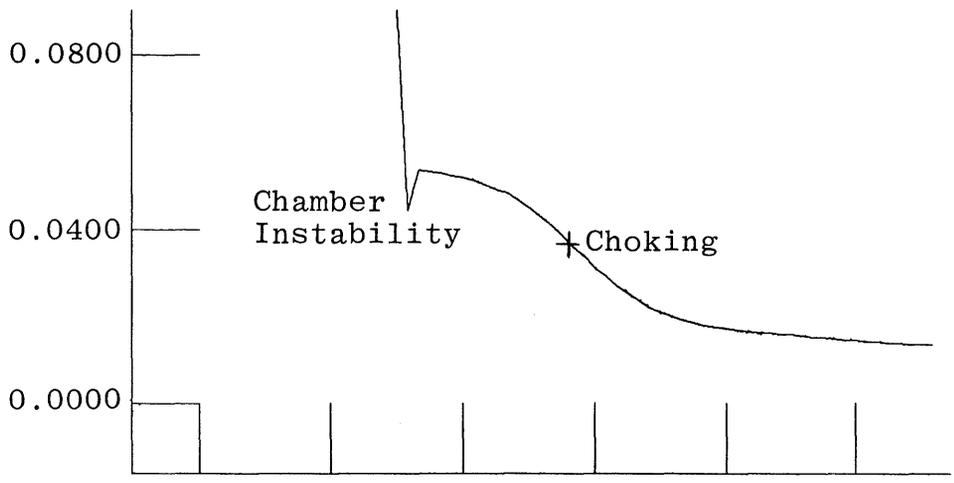
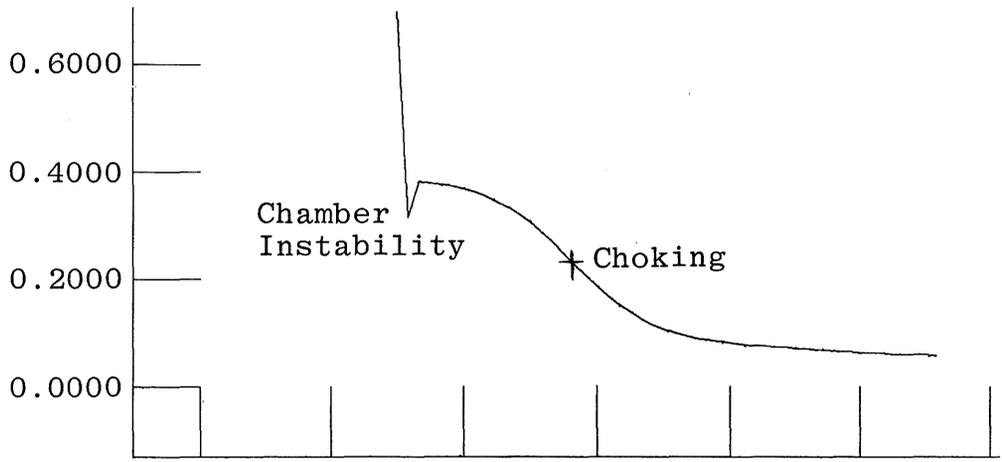
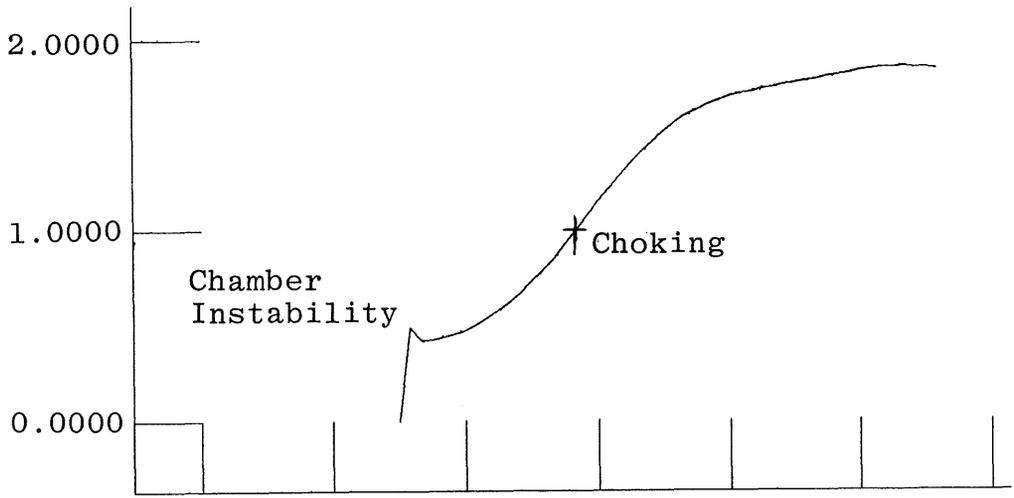


Figure 30 (Continued)

Initially, the chamber pressure is so low that separation occurs (Figures (31) and (32)). The chamber pressure was then increased in order to generate a normal shock in the nozzle. As the chamber pressure is increased further, the stationary position of the shock moves toward the aft end of the nozzle. The Rankine-Hugoniot equations were again obeyed.

Re-entry Vehicle (RV)

A re-entry vehicle was examined under inviscid and viscous conditions at hypersonic speeds ($M = 22$). Figures (33) and (34) illustrate the bow shock and region of undisturbed flow for both the inviscid and viscous cases. In the latter case, the influence of viscosity is seen in the development of a laminar boundary layer on the surface and a vortex being formed in the rear of the RV.

M-117 Warhead

The aerodynamic characteristics of an M-117 warhead were examined under subsonic, transonic and supersonic inviscid conditions. Four free stream Mach conditions were studied: $M_\infty = 0.5$, $M_\infty = 0.88$, $M_\infty = 1.14$ and $M_\infty = 1.80$. Figures (35) through (37) represent contours for the four cases stated above. Figures (38) and (39) illustrate the pressure coefficients for the subsonic and transonic cases and results are compared with experiment.

3.4 Diffusion

The time dependent diffusion equation for heat conduction (energy equation), magnetic diffusion (induction equation) and viscous transport (momentum equation) was solved.

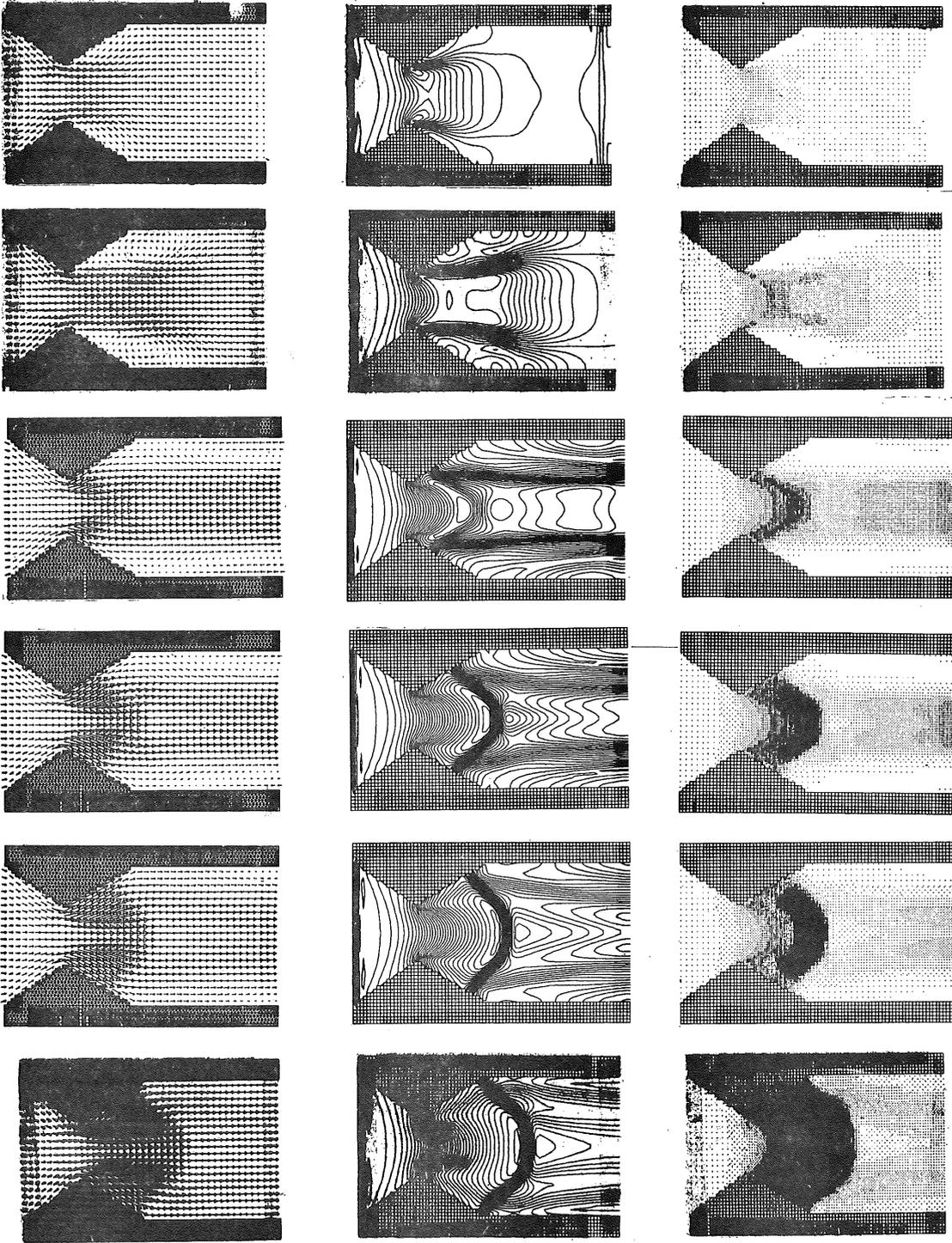
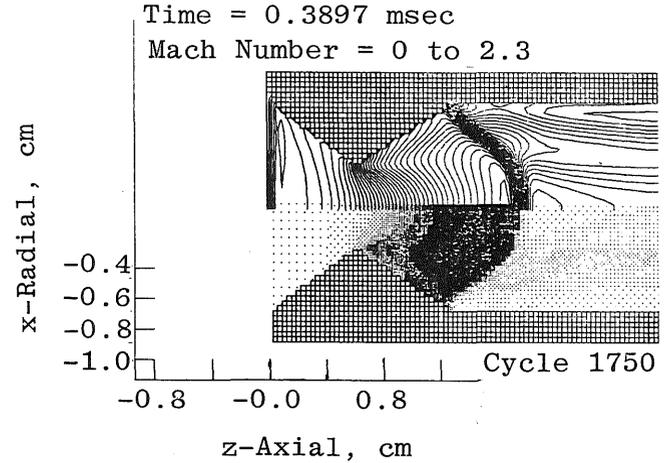
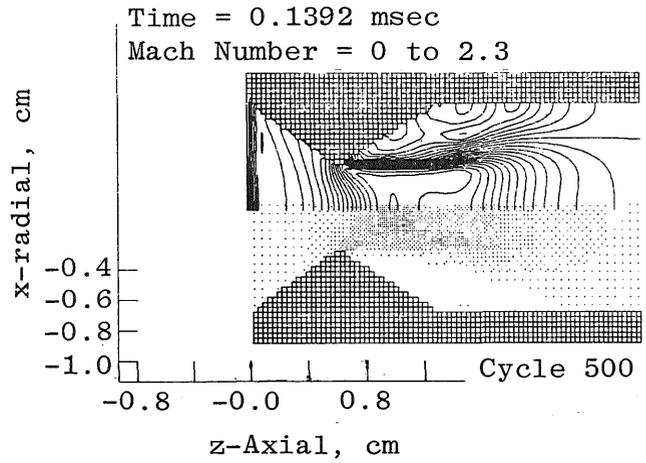


Fig. 31 Transient Nozzle Flow, Separation and Shock Formation

Nozzle Flow
Linear



Nozzle Flow
Linear

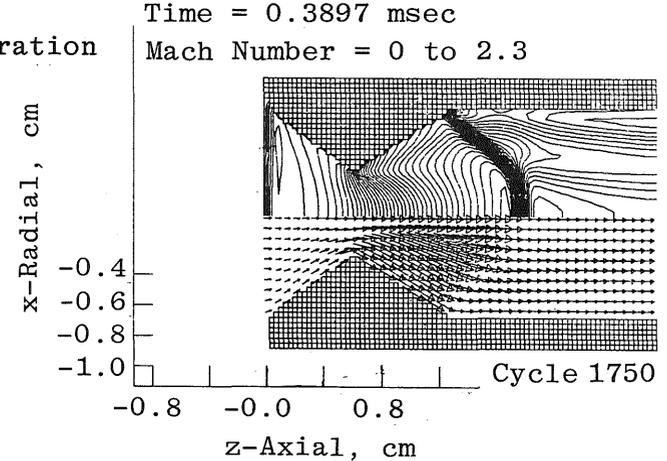
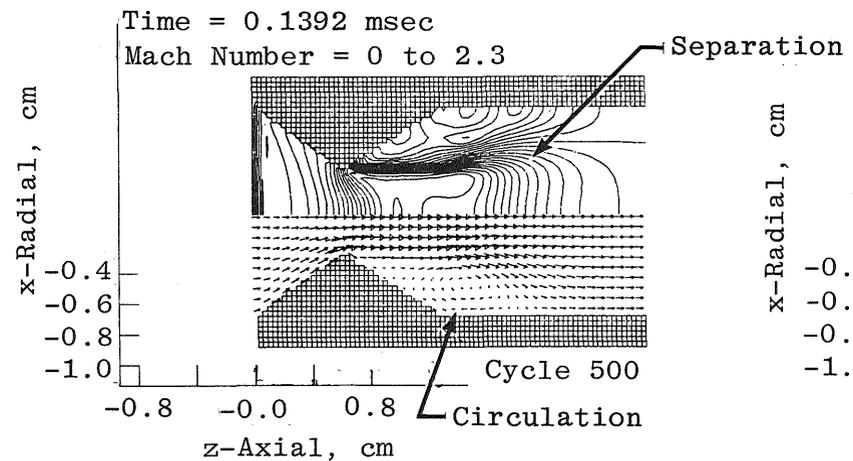


Fig. 32 Nozzle Separation and Shock Formation. Mach Contours and Mach Shading (Above) and Mach Contours and Velocity Vectors (Below)

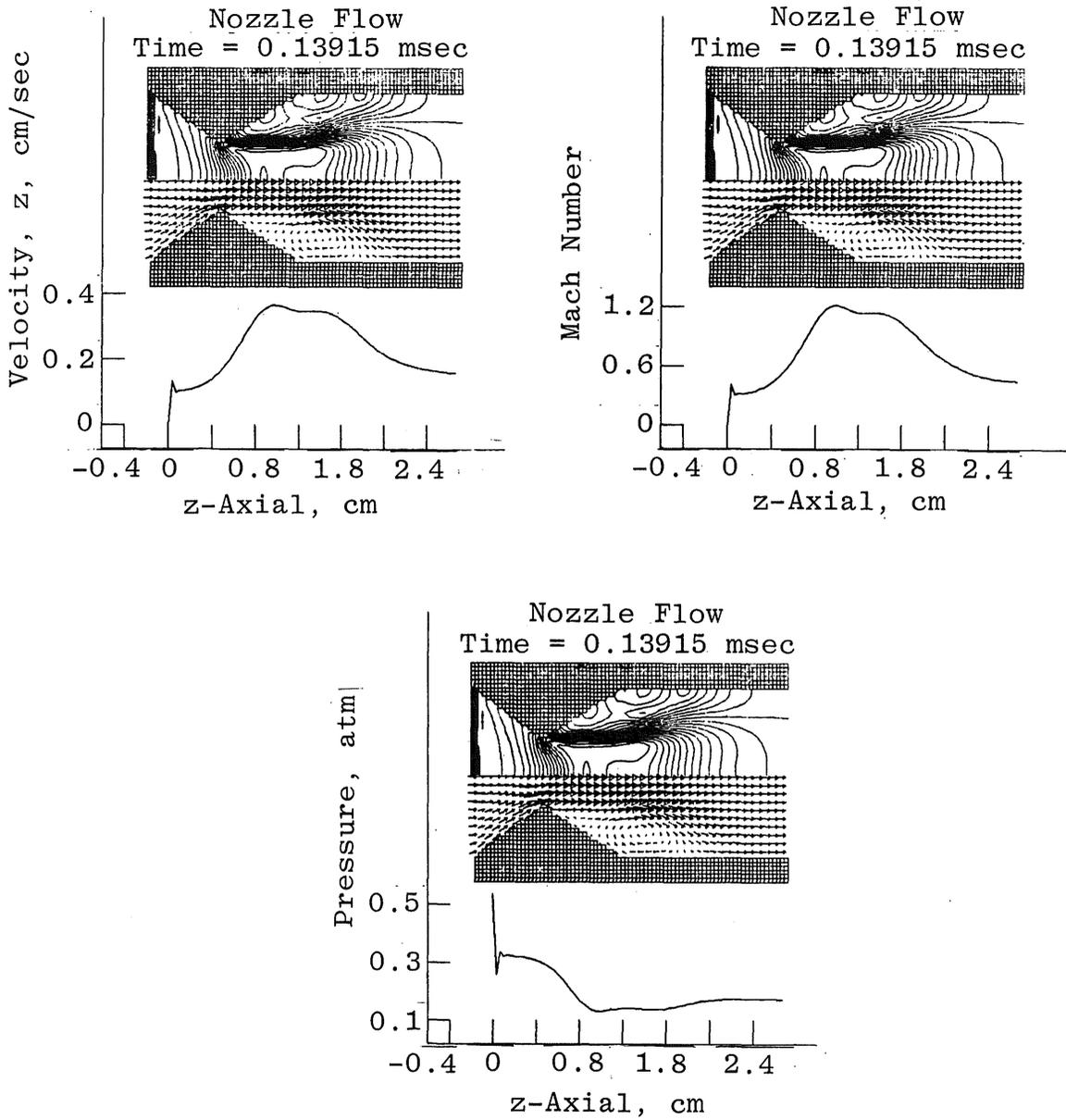


Figure 32 (Continued)

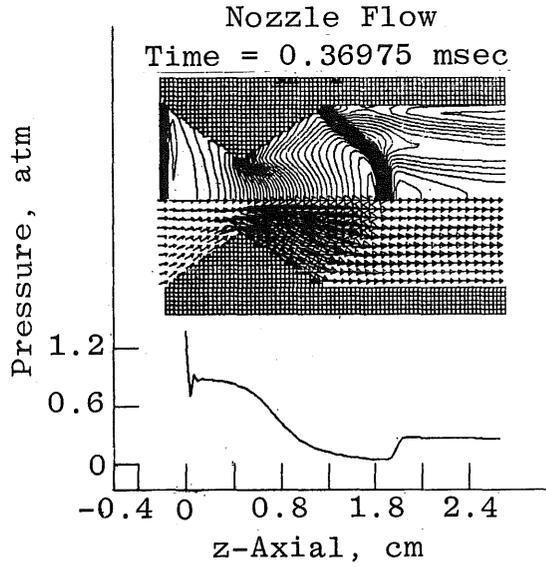
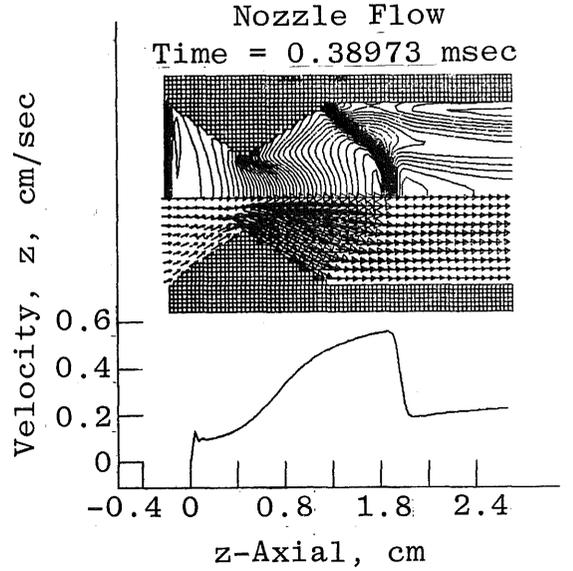
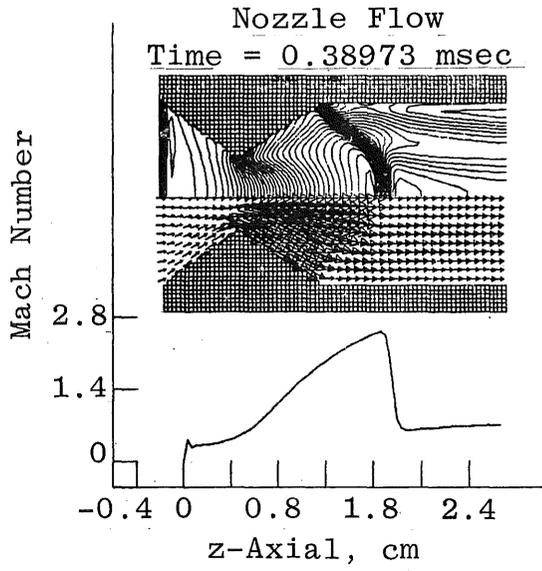


Fig. 32 (Continued)

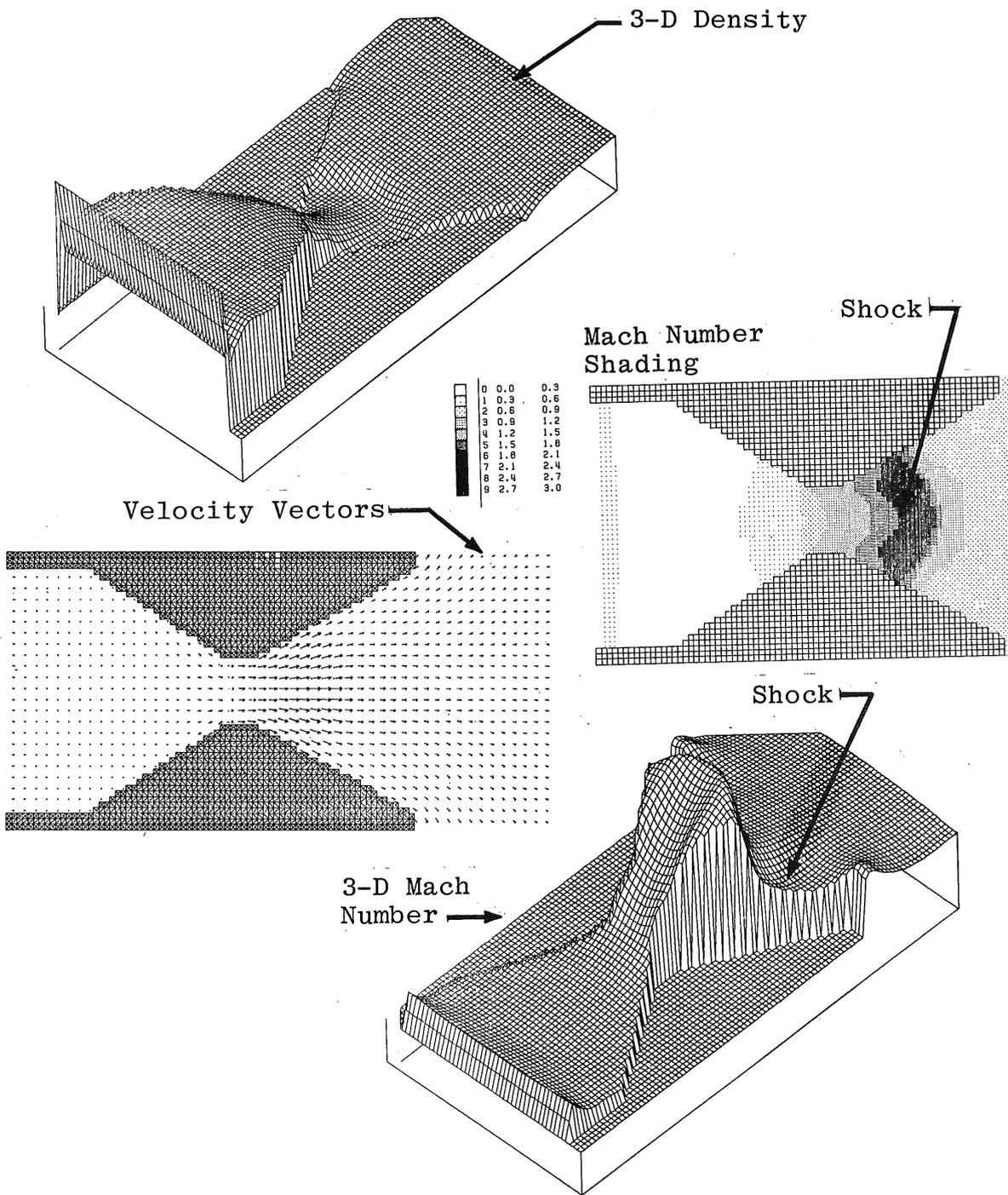


Fig. 32 (Continued)

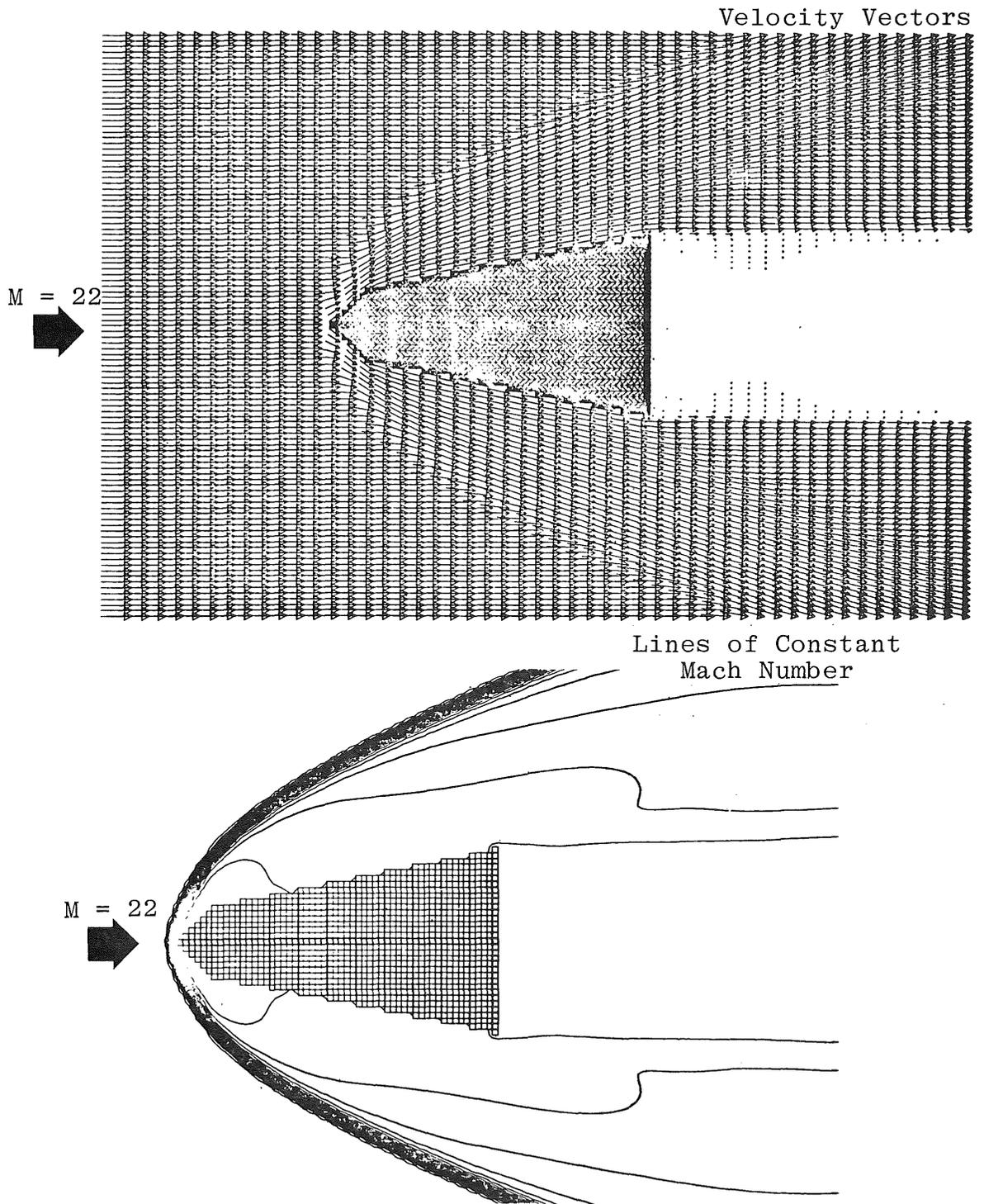


Fig. 33 Re-Entry Vehicle Inviscid Solutions

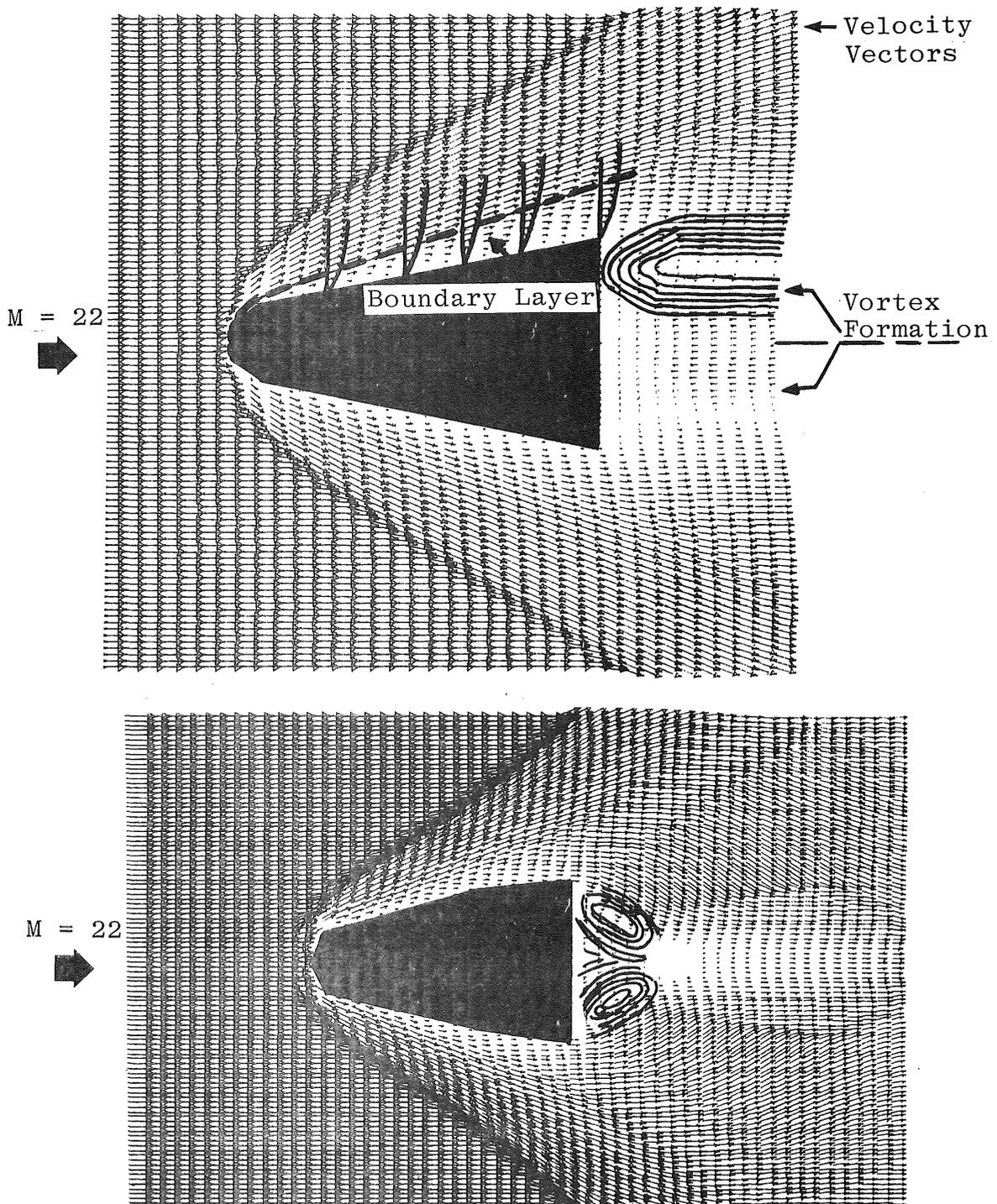


Fig. 34 Re-Entry Viscous Solutions

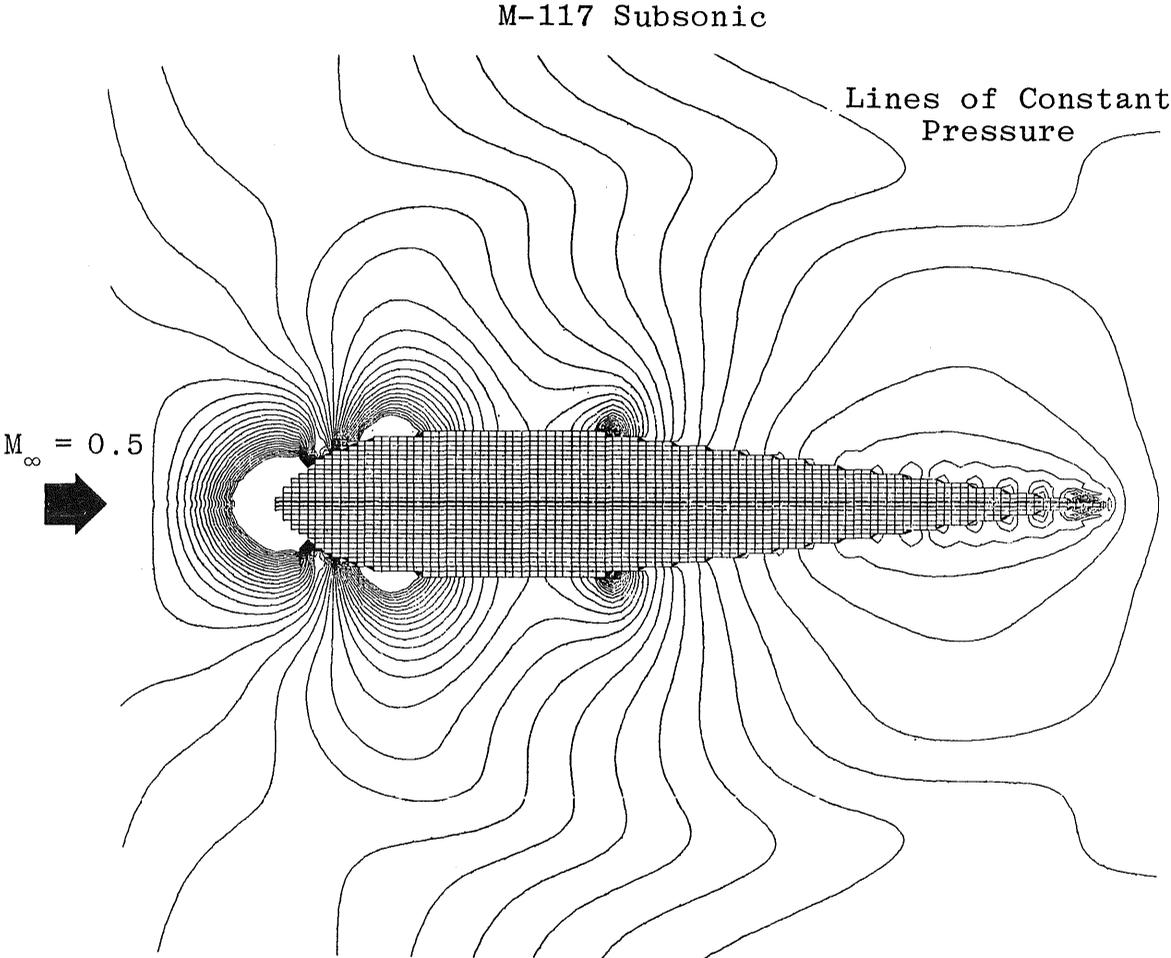


Fig. 35 M-117 Pressure Contours, $M_\infty = 0.5$

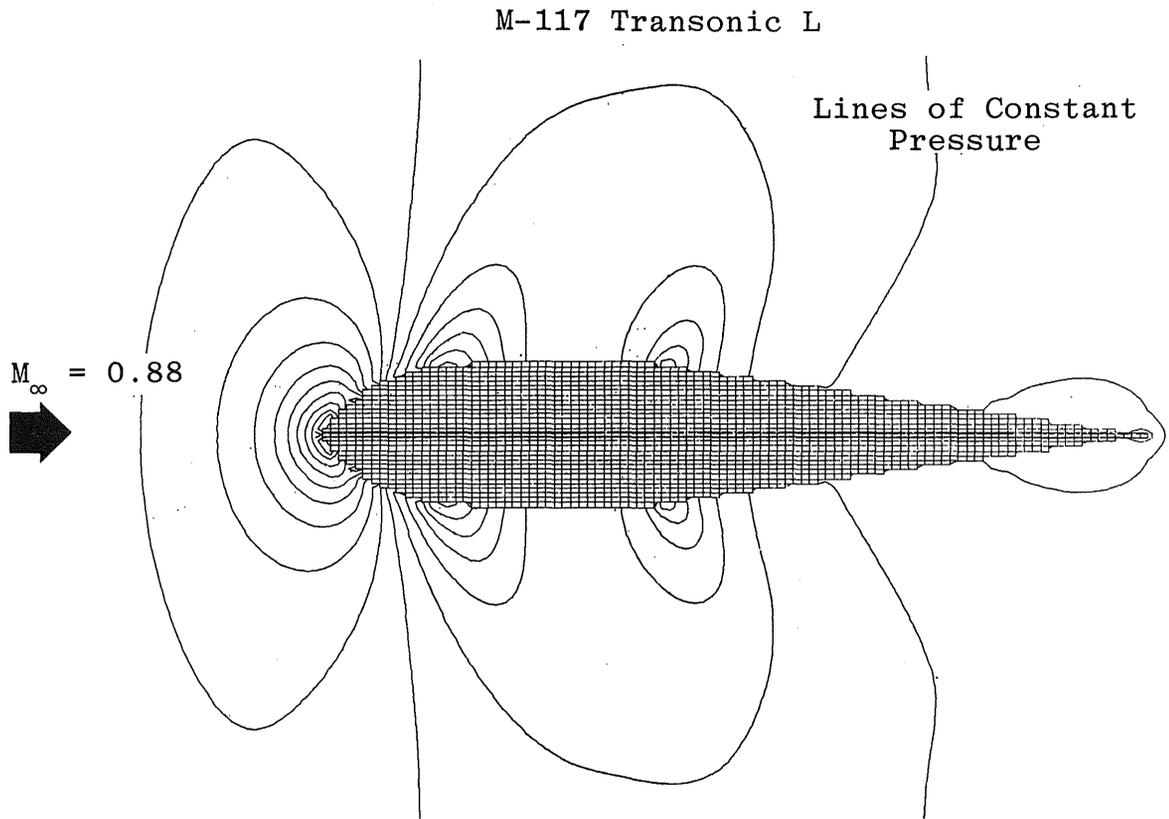


Fig. 36 M-117 Pressure Contours, $M_\infty = 0.88$

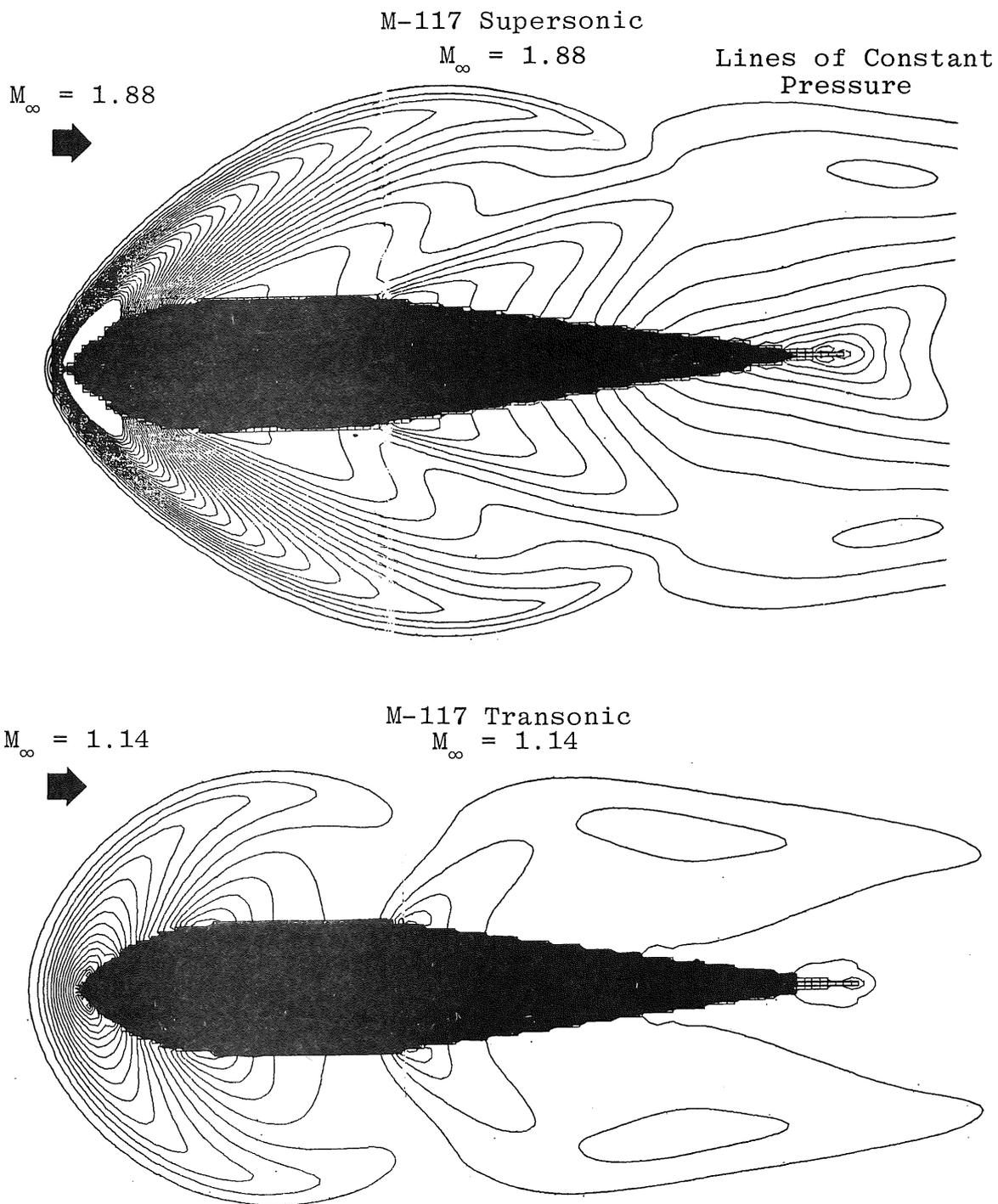


Fig. 37 M-117 Pressure Contours, $M_\infty = 1.14$ and $M_\infty = 1.88$

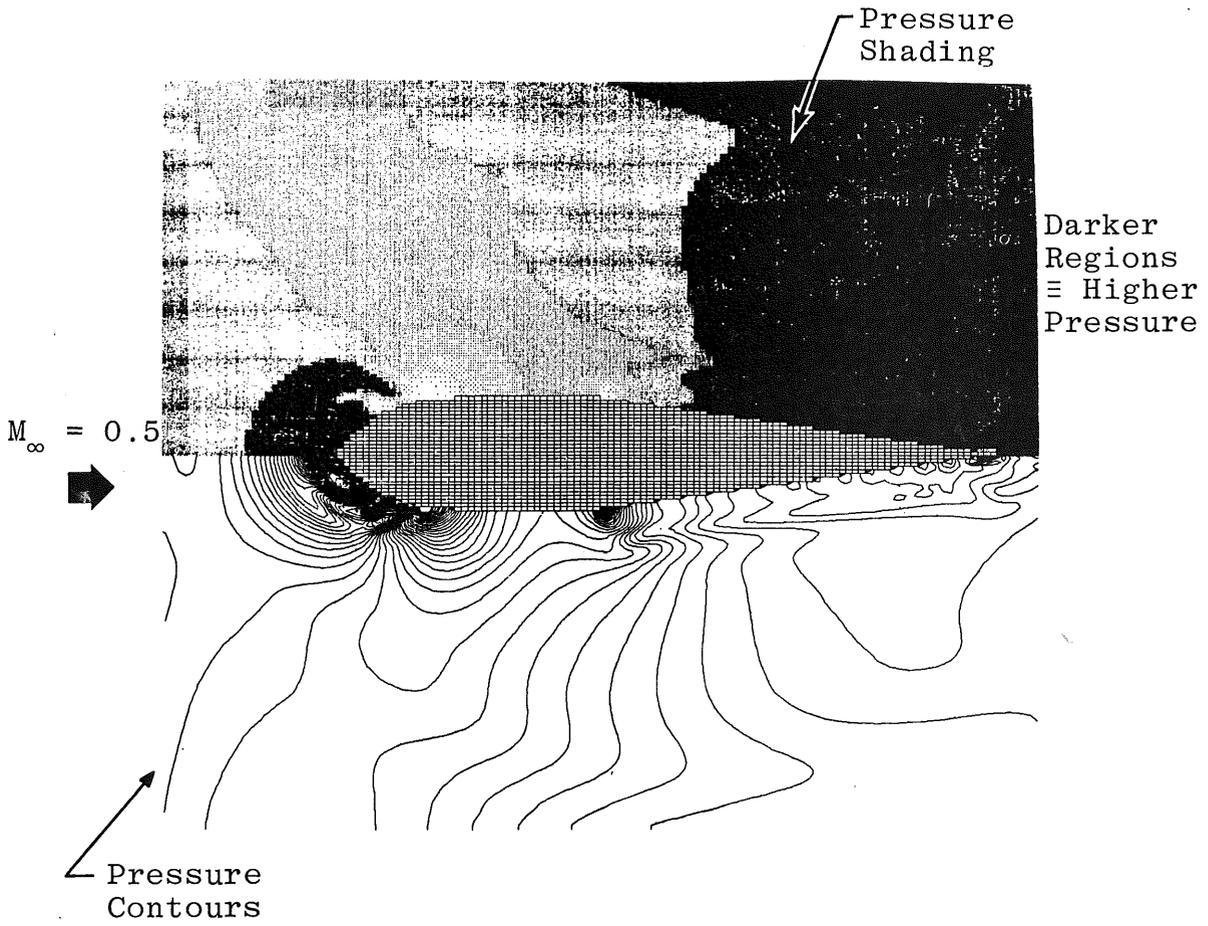


Fig. 37 (Continued)

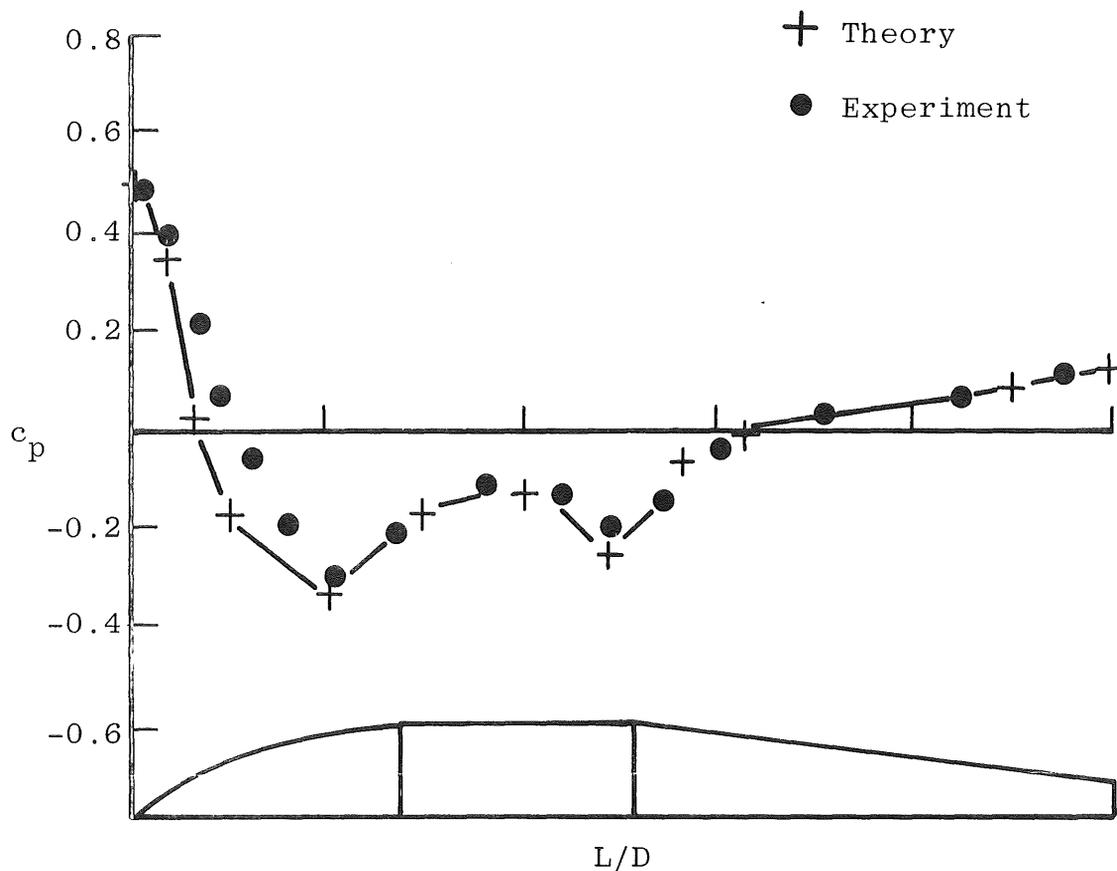


Fig. 38 M-117 Pressure Coefficient, $M_\infty = 0.5$

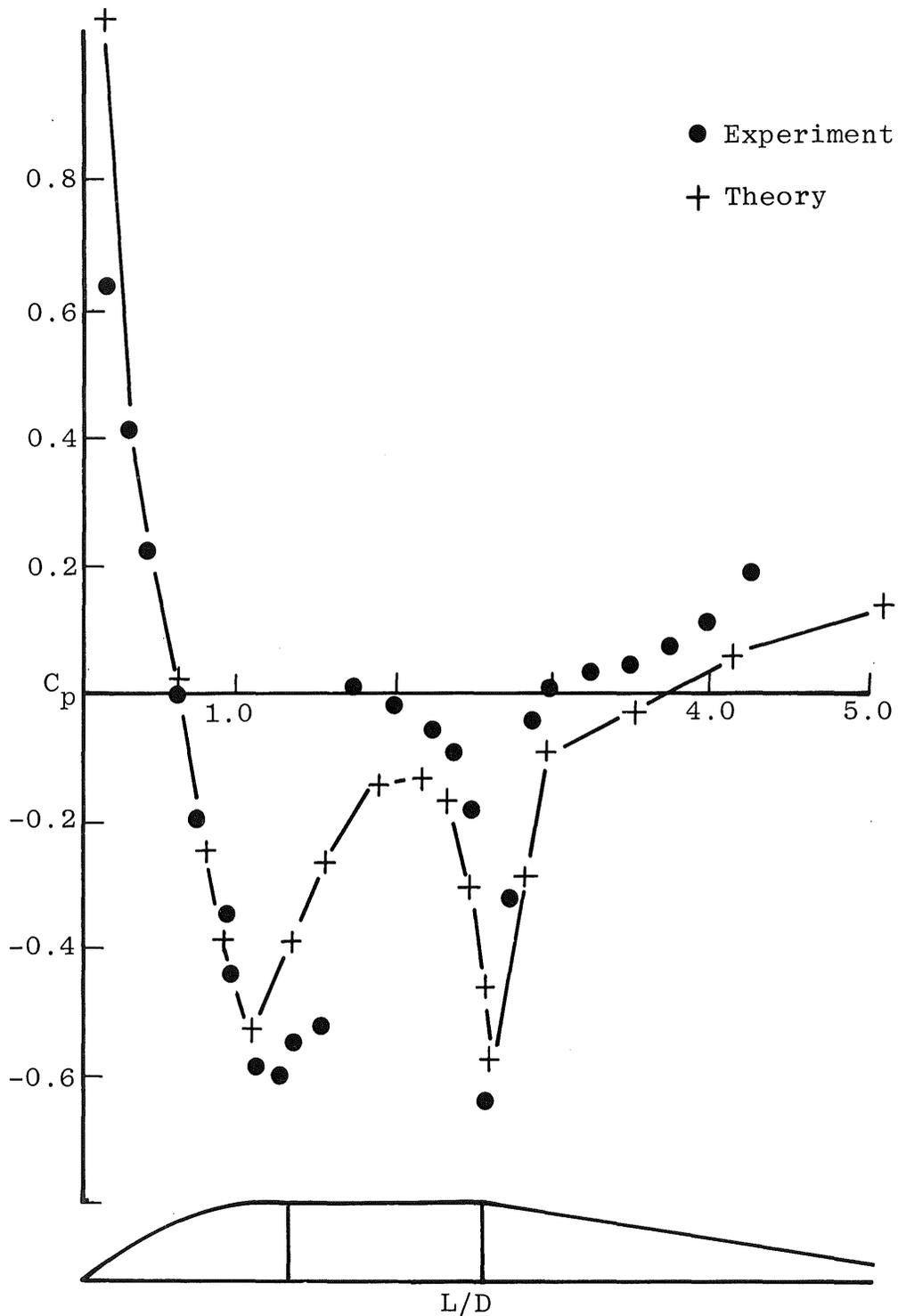


Fig. 39 M-117 Pressure Coefficient, $M_\infty = 0.88$

Examining the momentum, energy and induction equations and eliminating all convective ($\bar{v} \cdot \nabla$) and hydrodynamic (∇p) effects, the one-dimensional equations reduce to:

$$\frac{\delta}{\delta t}(u) = \frac{1}{\rho} \frac{\delta}{\delta r} \left(\frac{\delta}{\delta r}(u) \right) \quad (211)$$

$$\frac{\delta}{\delta t}(T) = \frac{1}{\rho C_v} \frac{\delta}{\delta z} \left(\lambda \frac{\delta}{\delta z}(T) \right) \quad (212)$$

$$\frac{\delta}{\delta t}(B_\theta) = \frac{\delta}{\delta z} \left(\frac{1}{\sigma \mu_p} \frac{\delta}{\delta z}(B_\theta) \right) \quad (213)$$

Allowing for the diffusivities to be constant and equal to one:

$$\frac{\mu}{\rho} = 1 ; \frac{\lambda}{\rho C_v} = 1 ; \frac{1}{\sigma \mu_p} = 1 \quad (214)$$

Equations (211), (212) and (213) become identical and result in similar solutions for the same initial and boundary conditions.

For example, given a body, initially at an internal temperature of 100°K and an external (environmental) temperature of 200°K as shown in Figure (40) it is desired to find the increase in internal temperature as a function of time. A closed form analytic solution to Equations (211) through (214) has been obtained for the time dependent problems posed above. In all cases, the transient solution agreed with the analytic results to any desired accuracy by refining the mesh and time step. Figure (40) and Table (5) illustrate the compatibility between the numerical results and the analytic solution. Identical results were obtained by solving the momentum and induction equations with analogous boundary conditions.

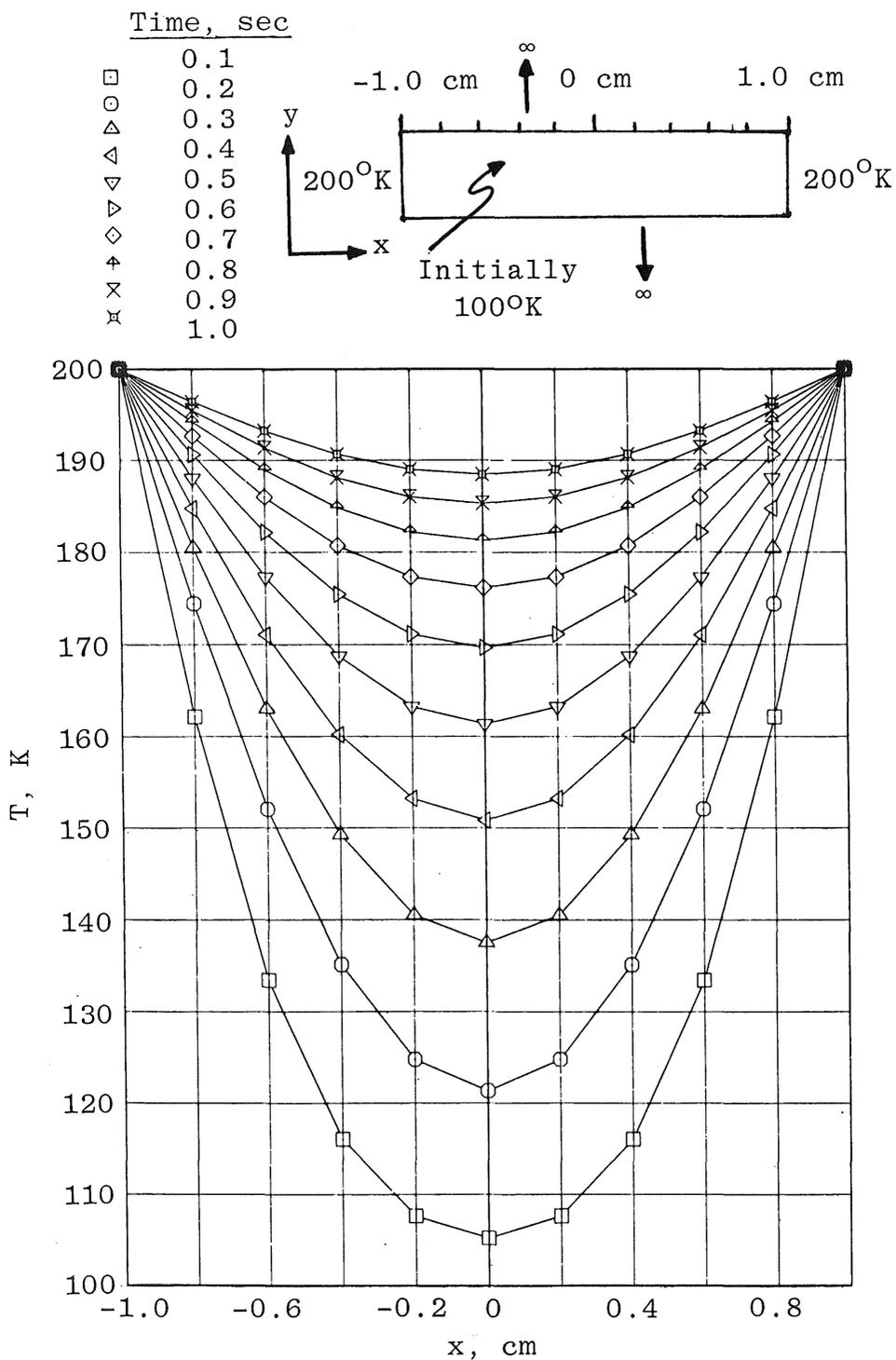


Fig. 40 Transient Thermal Diffusion

Table (5) Comparison between Numerical and Analytic Solutions for the Diffusion Equation.

CENTERLINE RESULTS										
TIME sec	NUMERICAL					ANALYTIC				
	U cm/sec	or	T °K	or	B gauss	U cm/sec	or	T °K	or	B gauss
0.0			100.0					100.0		
0.1			103.8					105.0		
0.2			121.6					122.0		
0.3			138.5					139.5		
0.4			152.0					152.0		
0.5			162.5					162.5		
0.6			170.7					170.5		
0.7			177.2					177.0		
0.8			182.2					182.0		
0.9			186.1					186.0		
1.0			189.1					189.0		

Finally, a pressure pulse was generated by disturbing the left boundary and allowing the sound wave to propagate to the right boundary, reflect, and return to the point of creation. Figure (41) illustrates this wave configuration moving at sound speed = $(\gamma P/\rho)^{1/2}$ or approximately 30,000 cm/sec.

3.5 Electric and Magnetic Fields

Solution to the equations of motion for a conducting fluid requires that the current and the magnetic and electric fields be known at every position within the fluid. As discussed in Section (2), for high magnetic Reynolds numbers, the current and electromagnetic fields are computed based on the magnetic induction equation and Ohm's Law. For flow with low magnetic Reynolds number, an electric potential or current stream function is used to calculate the electric field and current

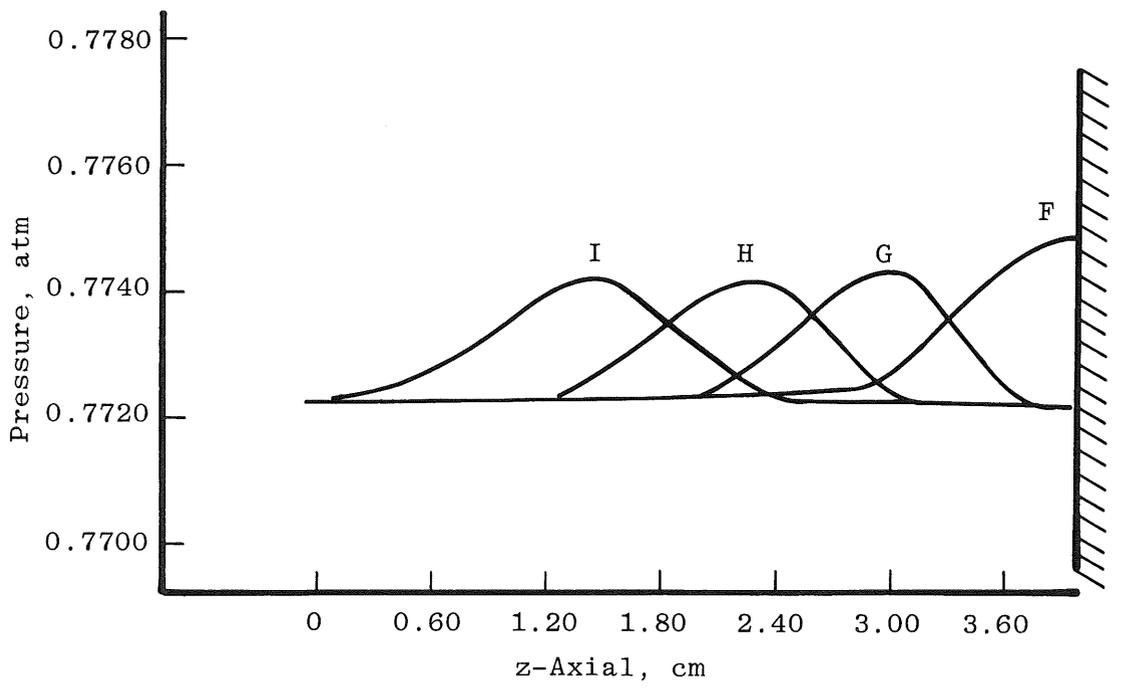
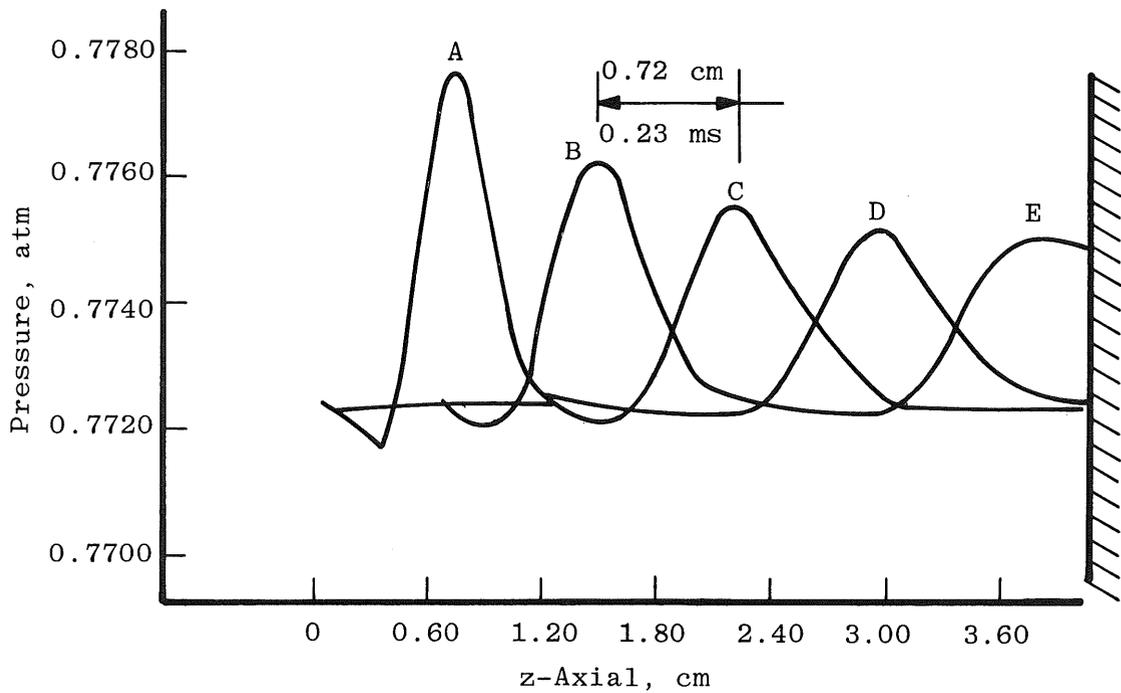


Fig. 41 Propagating Sound Wave

distribution where the induced magnetic field is considered negligible by virtue of its low magnetic Reynolds number.

Employing the finite difference equations and boundary conditions discussed in Section (2), several simple low magnetic Reynolds number problems were solved using the current stream function defined by Equation (65). Considering one electrode-pair with no Hall current, a solution to Equation (53) was attained, using the method of Successive Over-Relaxation. Based on this solution, the current vectors, the current stream function, the electric potential, were calculated and are shown in Figures (42) to (45). A calculation was performed for Hall Parameter = 5 with results shown in Figure (46). Figure (47) depicts the convergence of the current stream function. Finally, three electrode-pairs ($\beta = 2$) were analyzed in the same manner and results are graphically displayed in Figures (48) and (49).

Figures (50) through (53) show the transient current stream lines when a shock wave is passing through the single electrode-pair channel. As the shock enters the channel, an electric field is induced since the EMF ahead and behind the shock wave are different. Eddy currents are set up resulting from this electric field. However, the boundary conditions of the current stream function at the channel exit (and entrance) requires a uniform Ψ across the duct. In order to satisfy this boundary condition, a secondary current eddy is set up opposite the principal eddy induced by the shock wave. Figure (42) shows the undisturbed current streamlines and Figures (50) through (53) represent

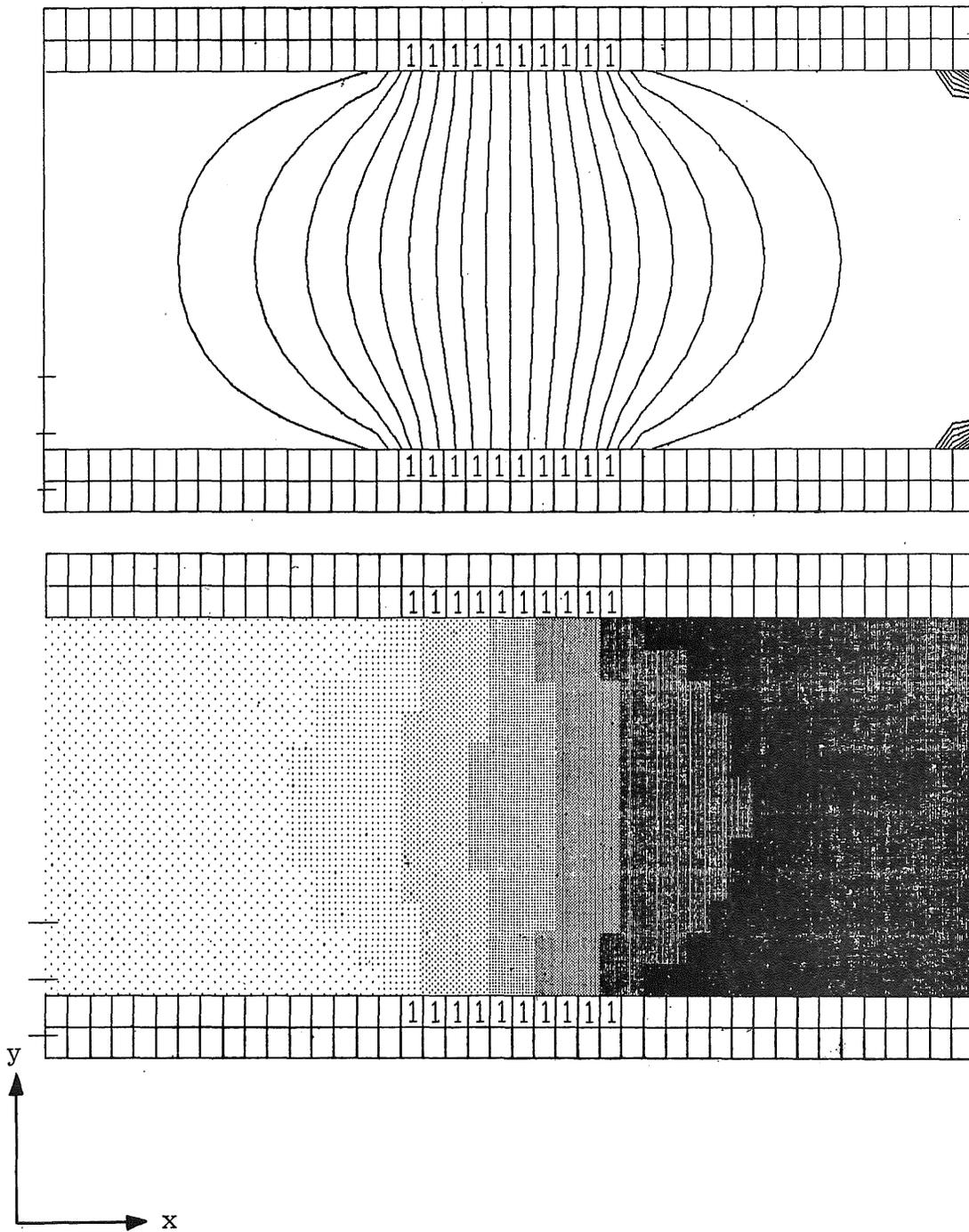


Fig. 42 One-Electrode Pair. Current Stream Function Contour and Shading Plots

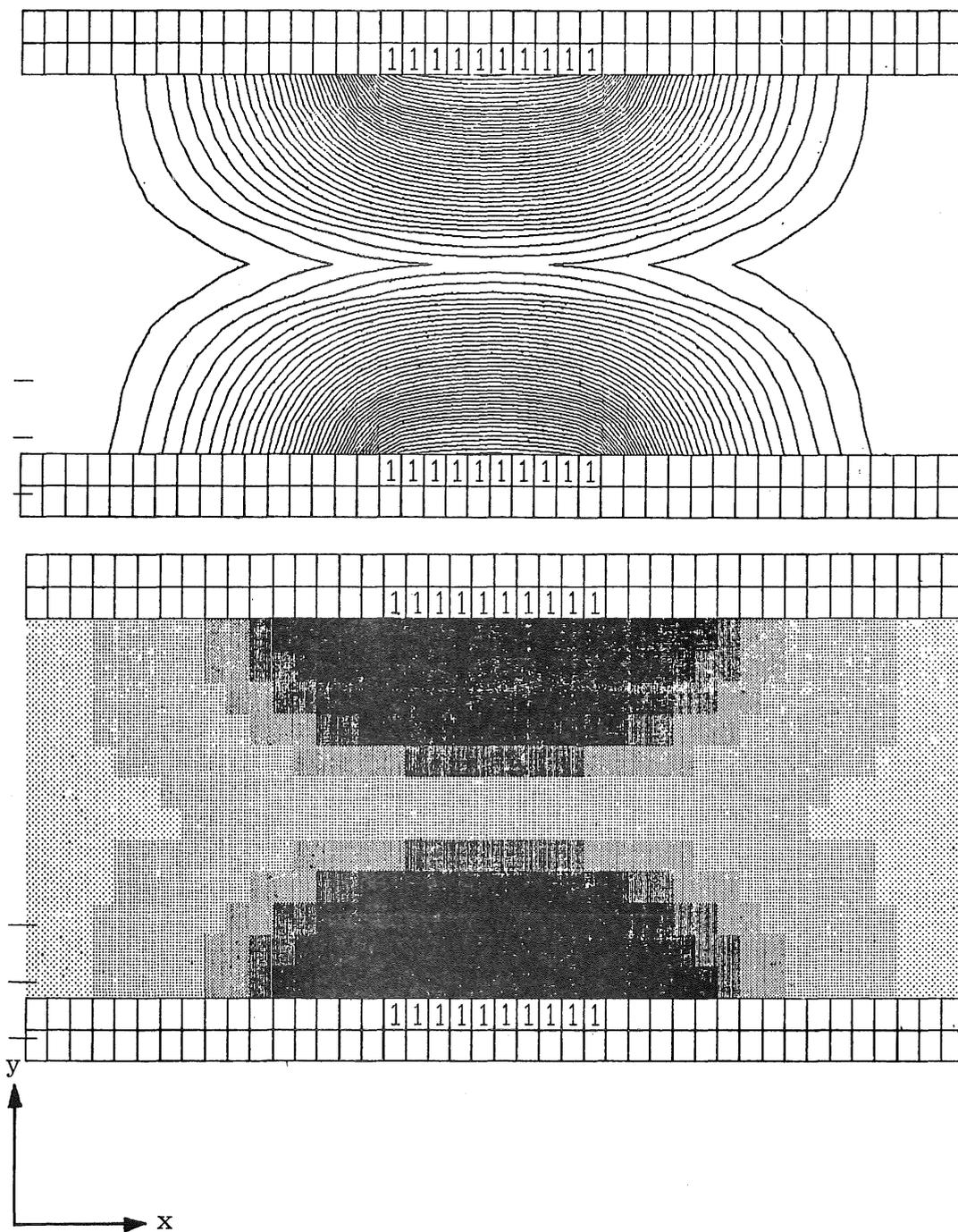


Fig. 43 One-Electrode Pair. Electric Potential Contours and Shading Plots

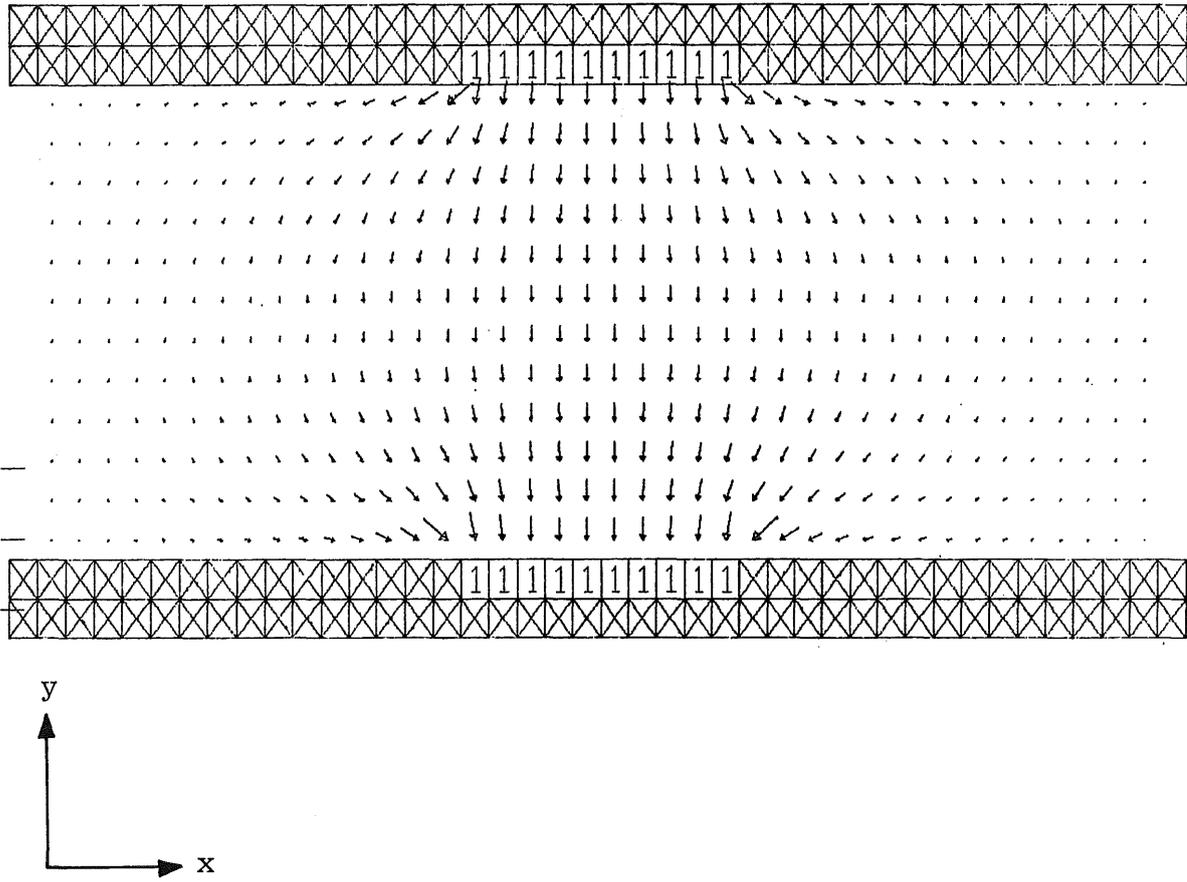


Fig. 44 One Electrode-Pair. Current Vectors.

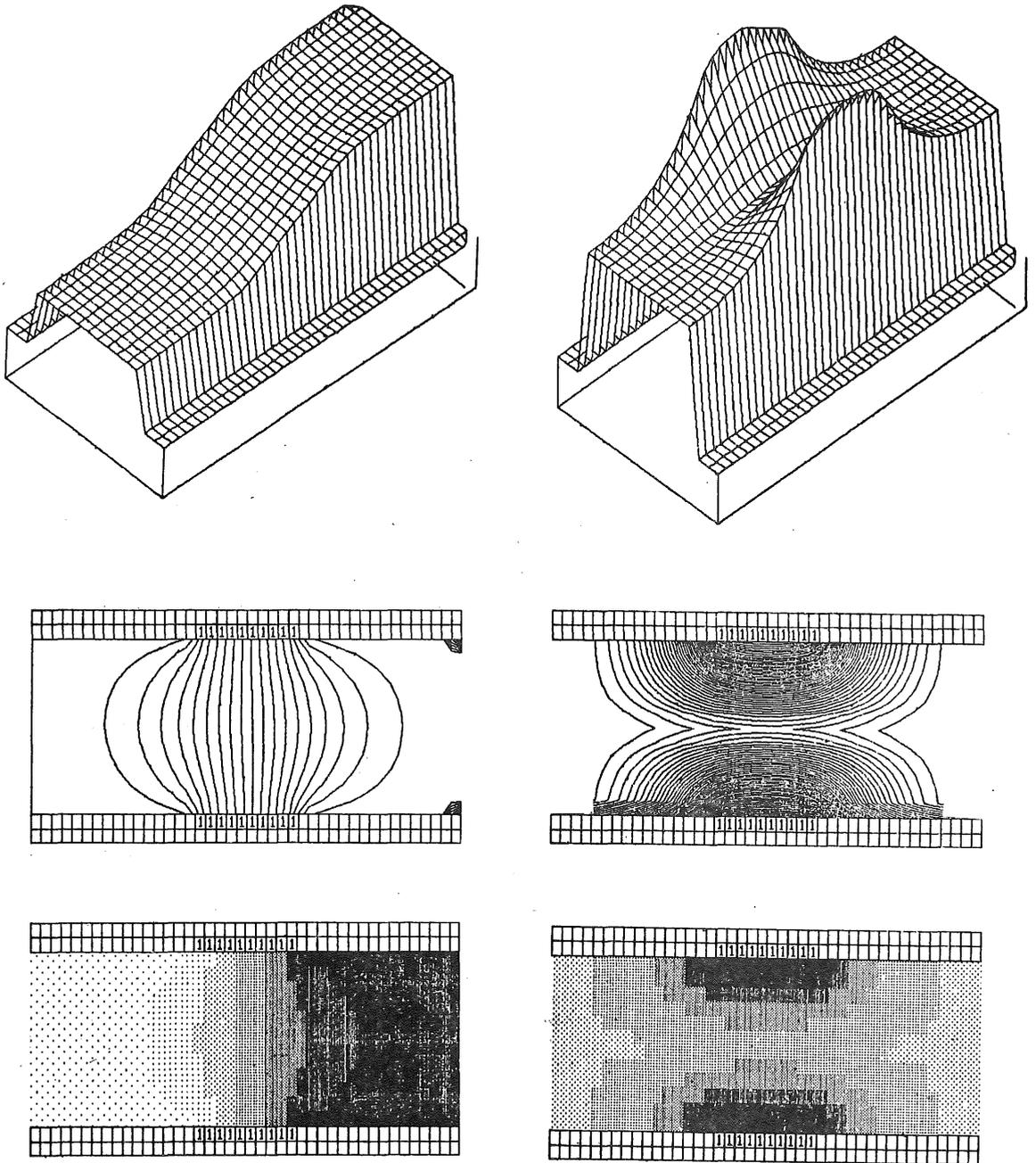


Fig. 45 One-Electrode Pair, 3-D Plots. Current Stream Function and Electric Potential

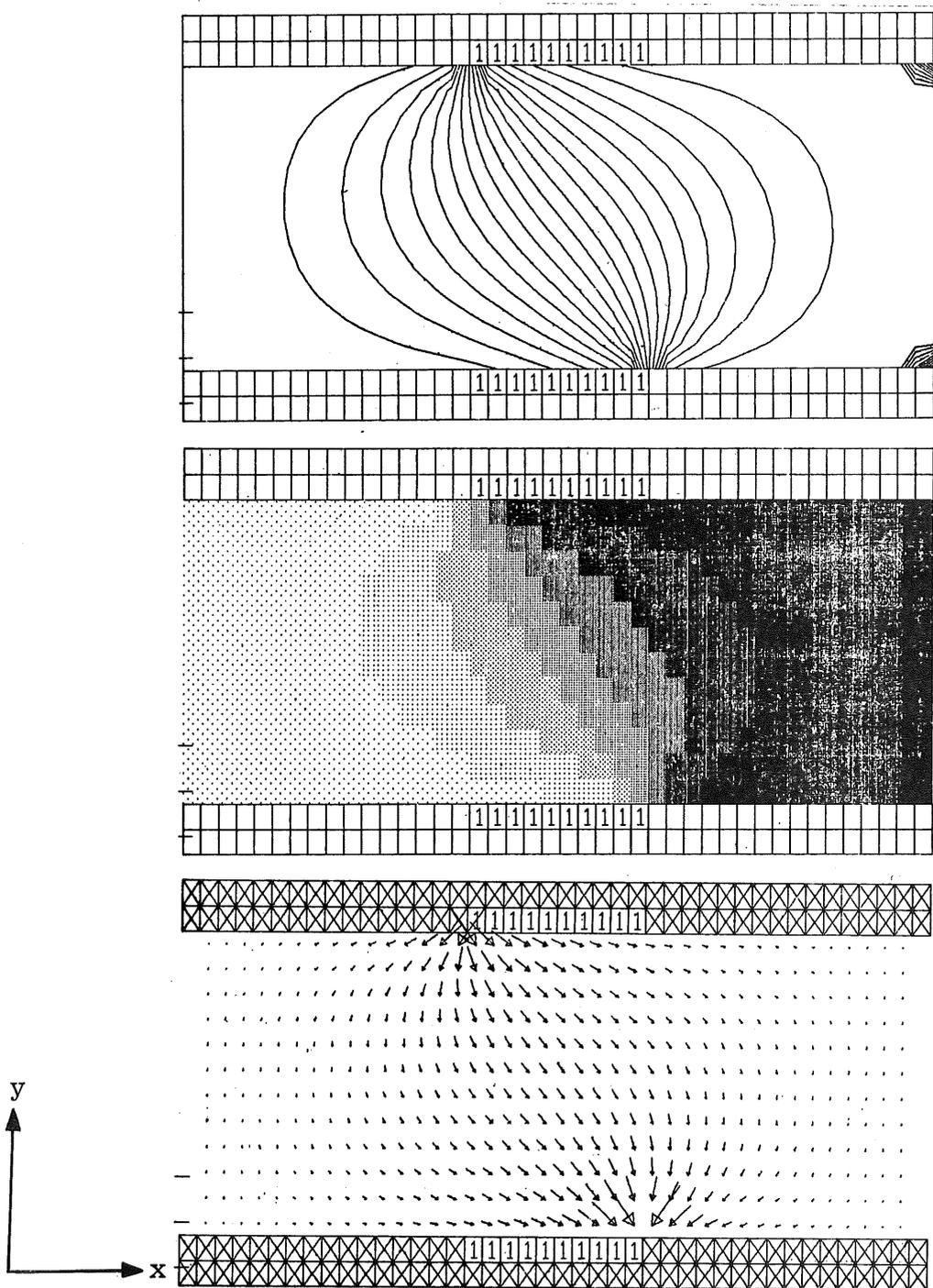


Fig. 46 One-Electrode Pair ($\beta = 5$). Current Stream Function and Current Vectors

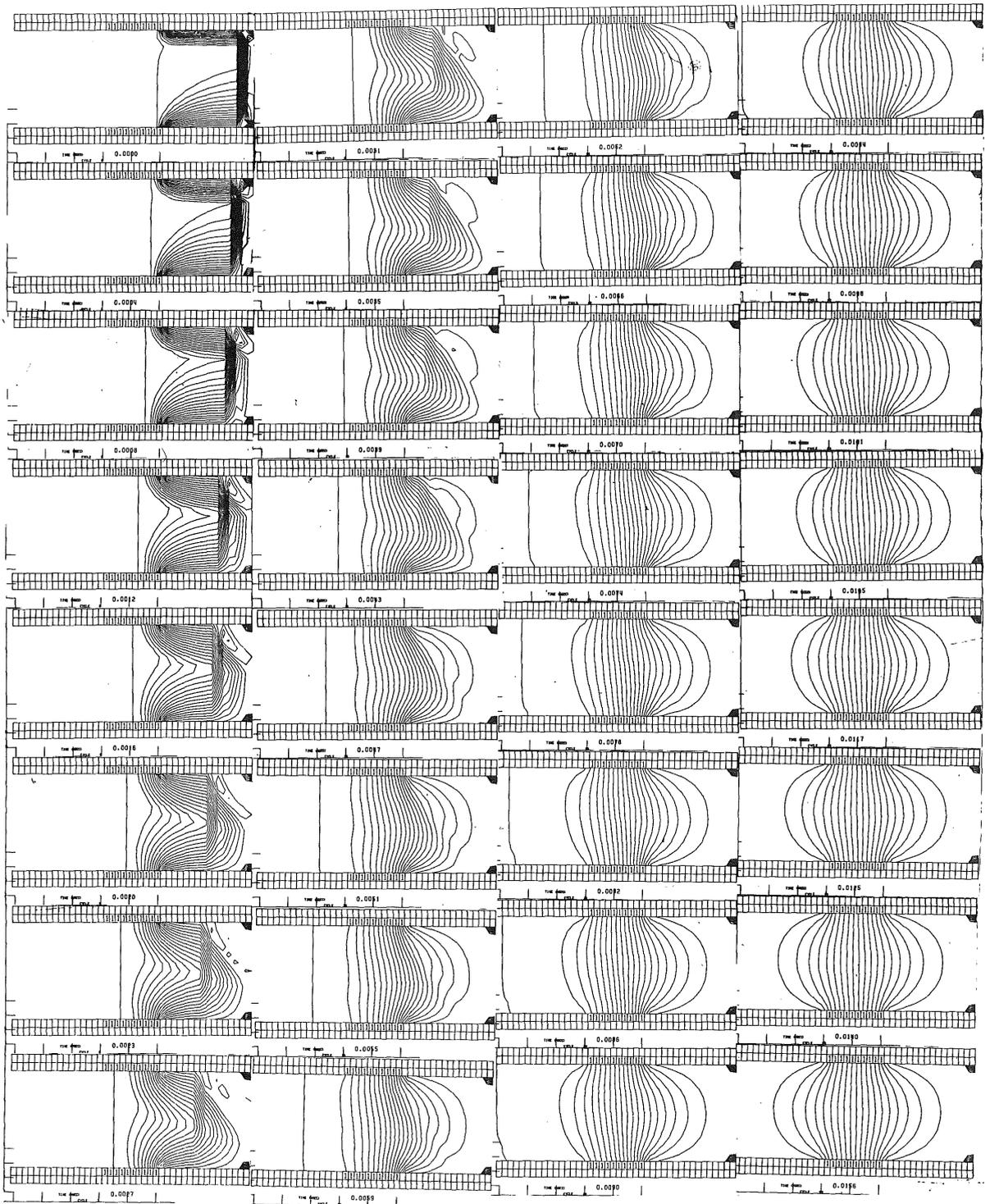


Figure 47 One-Electrode-Pair. Successive Over-Relaxation Iteration.

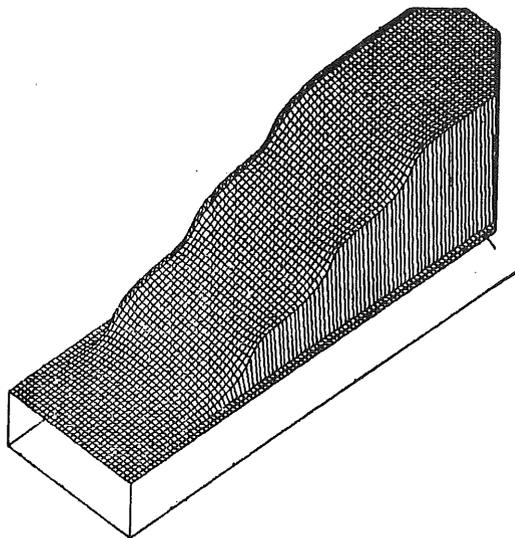
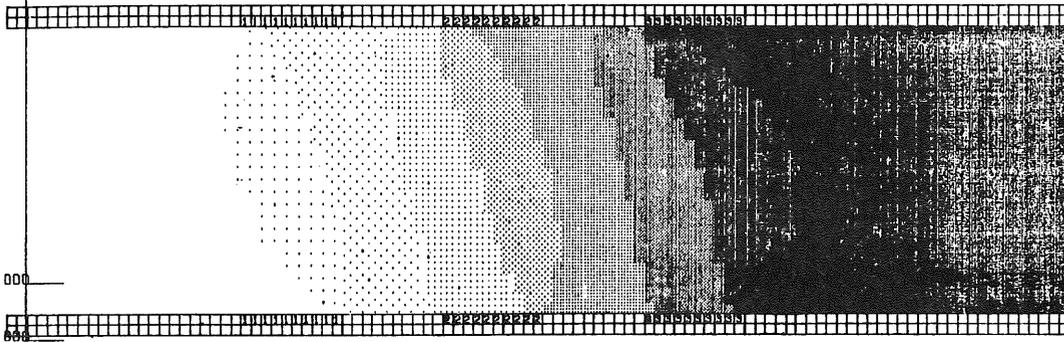
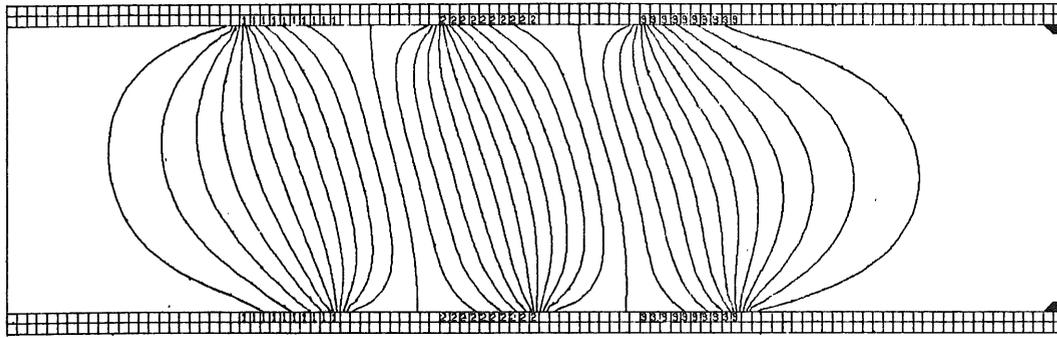


Figure 48 Three-Electrode-Pairs ($\beta = 2$). Current Stream Function.

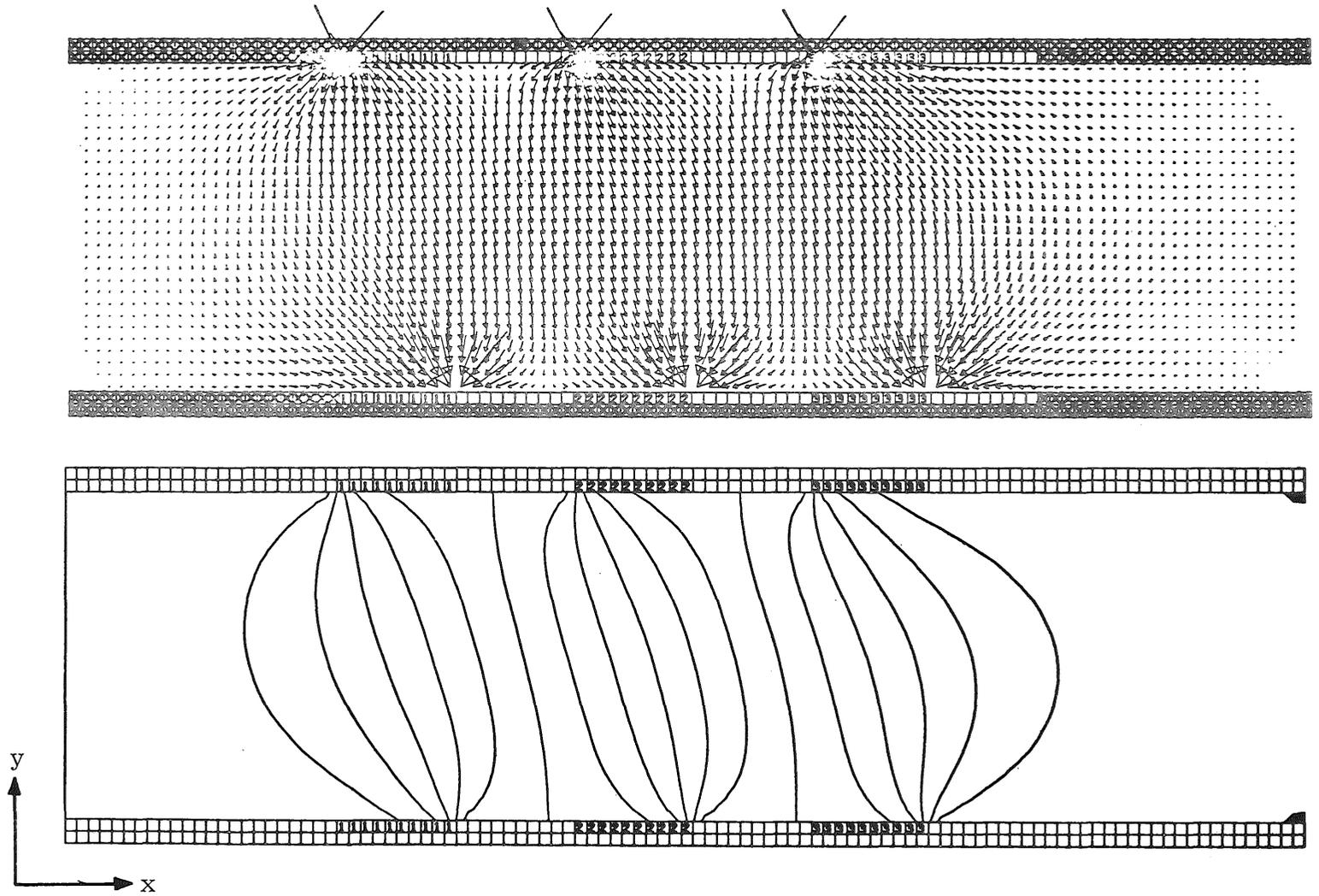


Fig. 49 Three Electrode-Pairs ($\beta = 2$).
Current Stream Function and Current Vectors

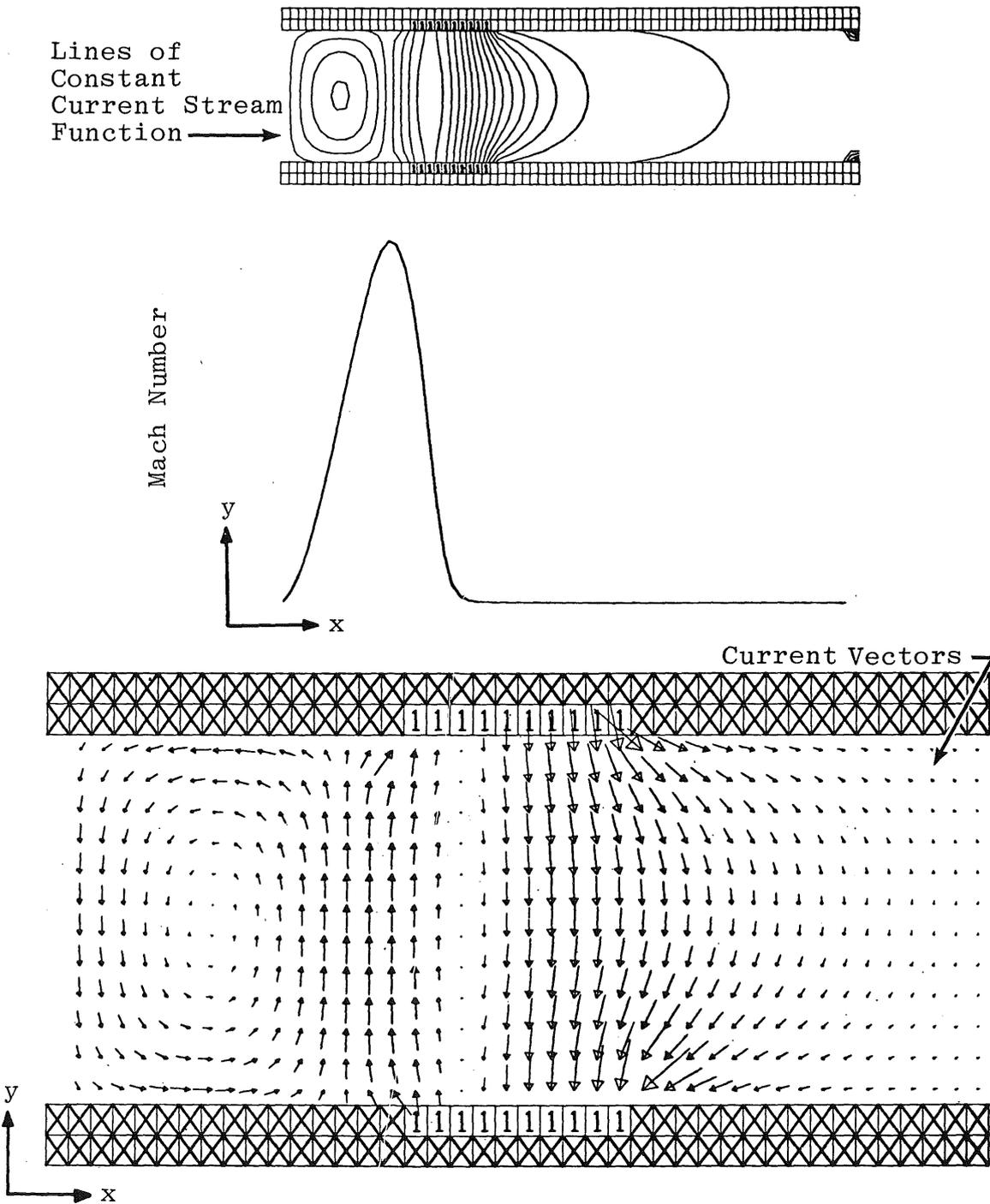


Fig. 50 Initial Formation of Current Eddies

Lines of Constant
Current Stream Function

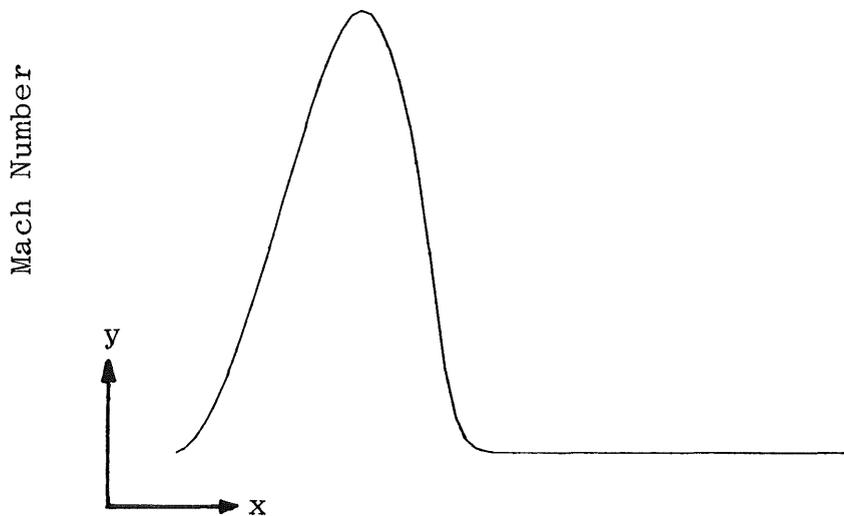
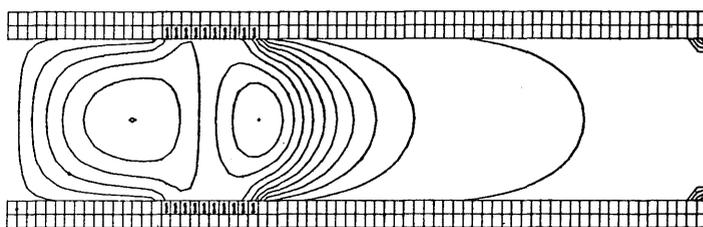
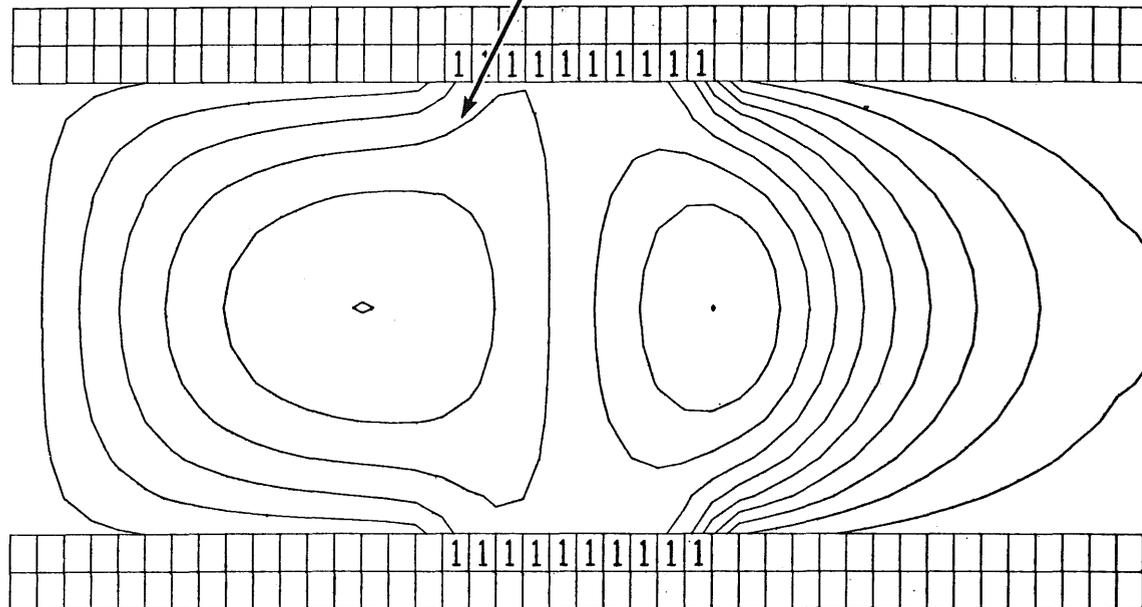


Fig. 51 Eddies in Motion with Shock Front

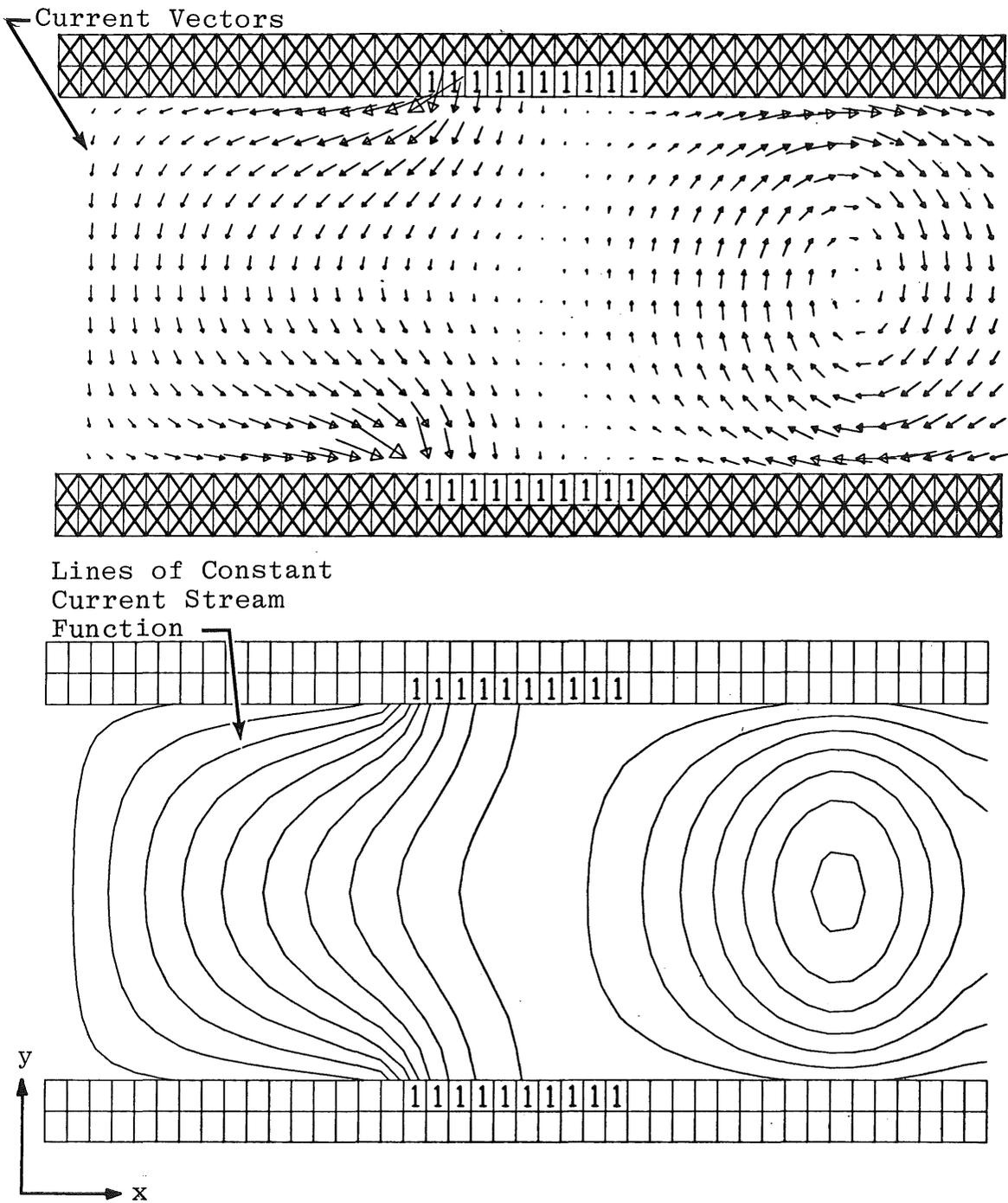


Fig. 52 Eddies Leaving the Channel

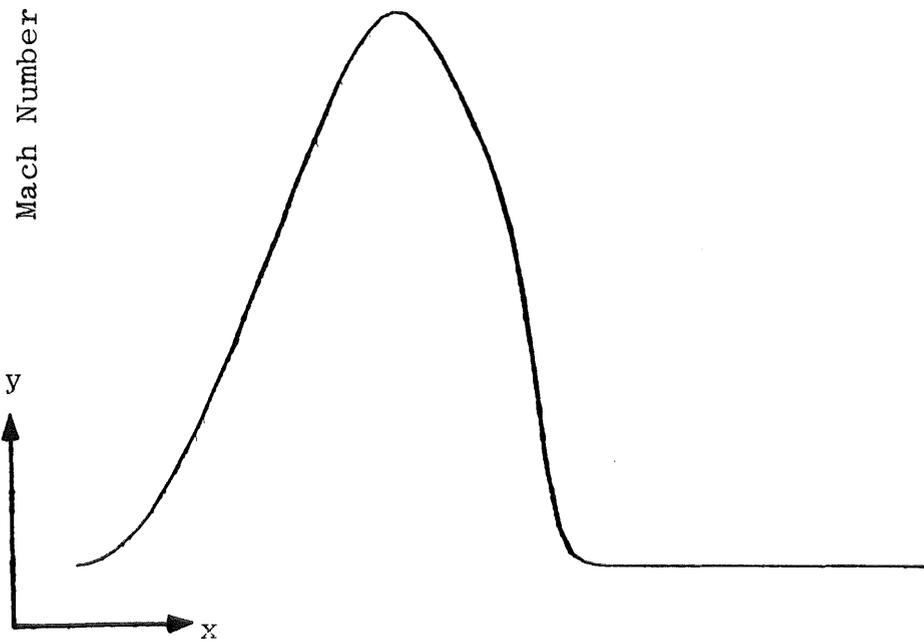
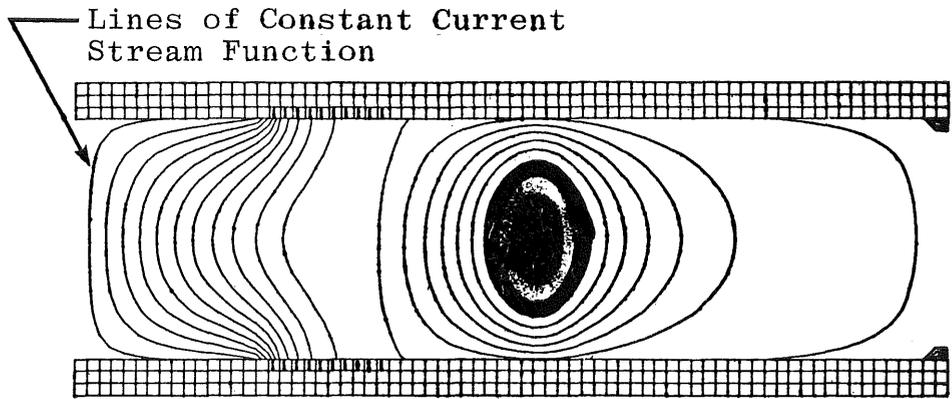


Fig. 53 Restoration of Initial Stream Current Function

different times as the shock wave passes through the channel. When the shock wave leaves the duct, the current stream function relaxes to its undisturbed initial state.

IV. MODELING OF AN MHD GENERATOR

The fundamental problems associated with modeling an MHD generator (Figure 54) concerns the treatment of:

- (1) gas dynamic effects such as shocks and boundary layers,
- (2) electromagnetic effects, and
- (3) the transient coupling between these two sets of fields.

In Section (3), gasdynamic and electromagnetic phenomena were examined independently through application to problems categorized as either strictly aerodynamic or electromagnetic in nature. The strong interaction between gasdynamic, viscous and electromagnetic forces will now be examined.

Demonstration of the influence of the Lorentz force ($\bar{j} \times \bar{B}$) on the flow field and, simultaneously, the influence of velocities and viscous shear on currents and electric fields is accomplished by investigating the following three cases (see Figure (55)):

(A) A nozzle-generator-diffuser system with five-electrode pairs is examined under inviscid conditions; emphasis is placed on modeling the entire energy conversion system. The applied magnetic field is shown in Figure (56) and design parameters are listed in Table (6).

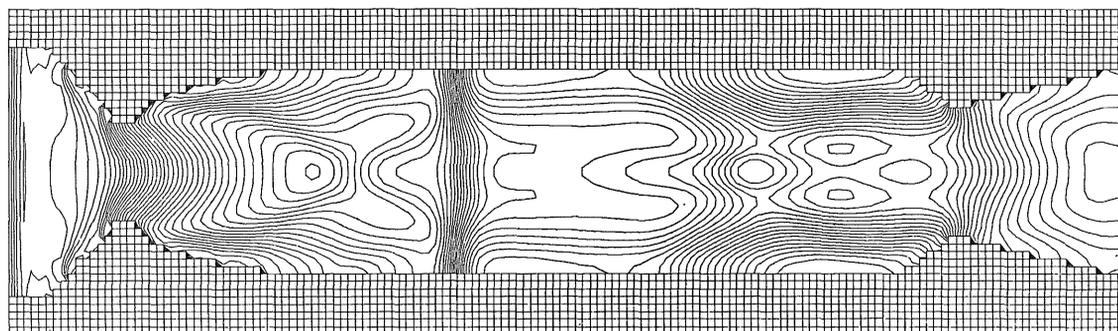
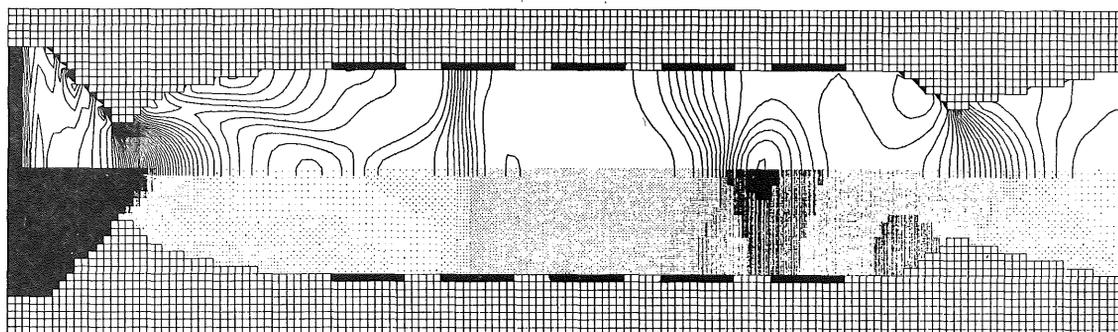
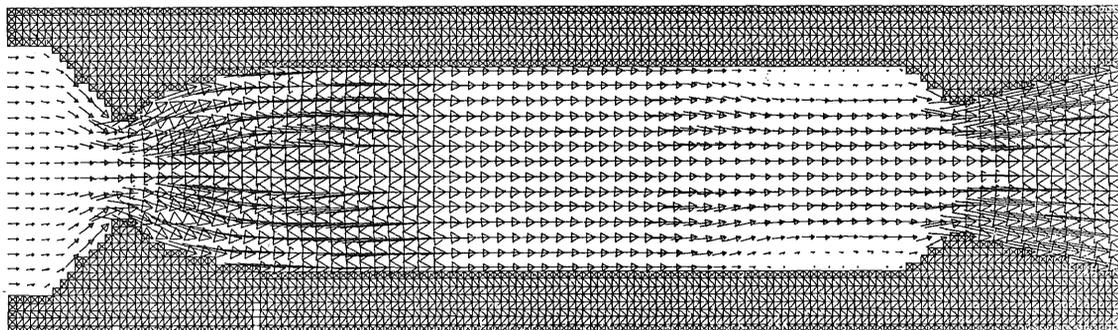


Figure 54 MHD Generator System

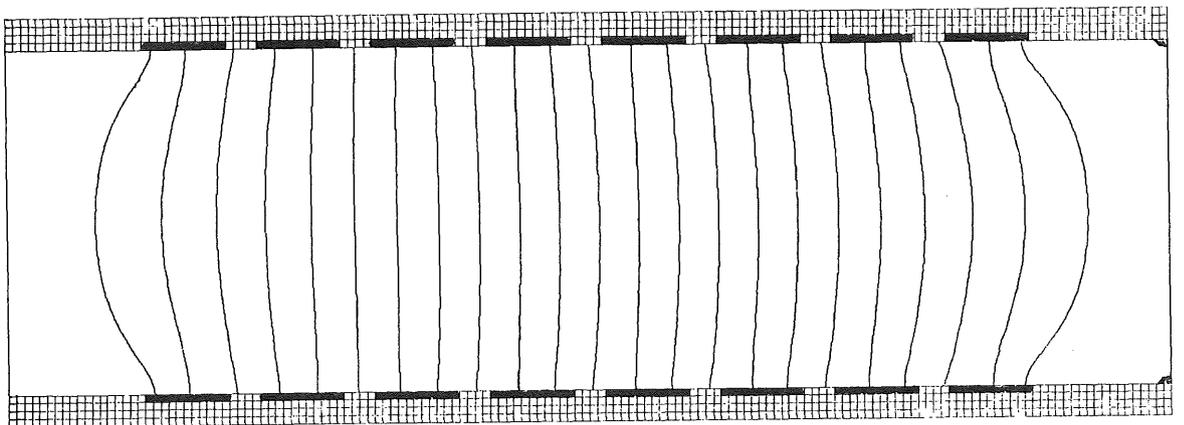
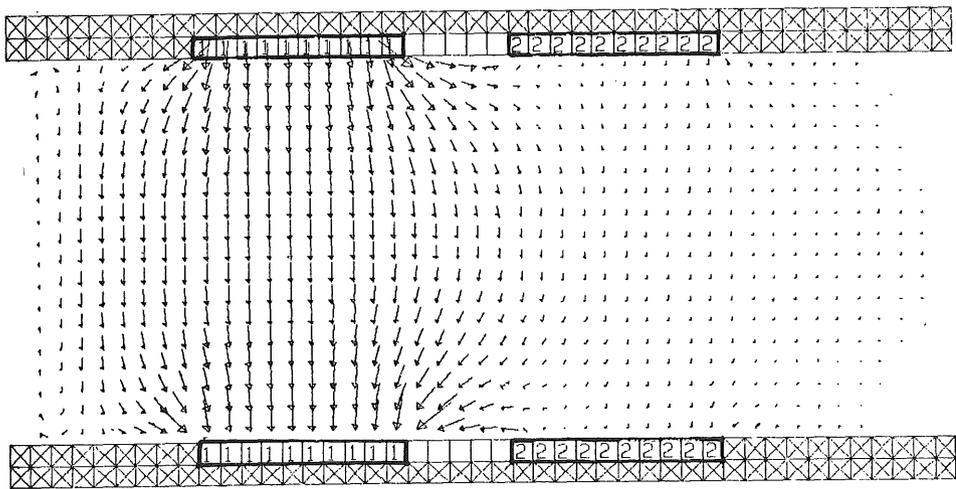
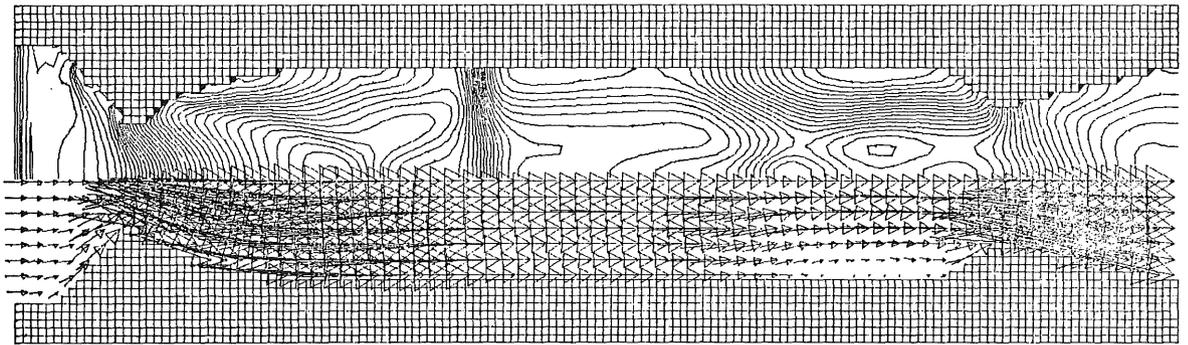


Figure 55 MHD Generator. Three Cases Modeled.

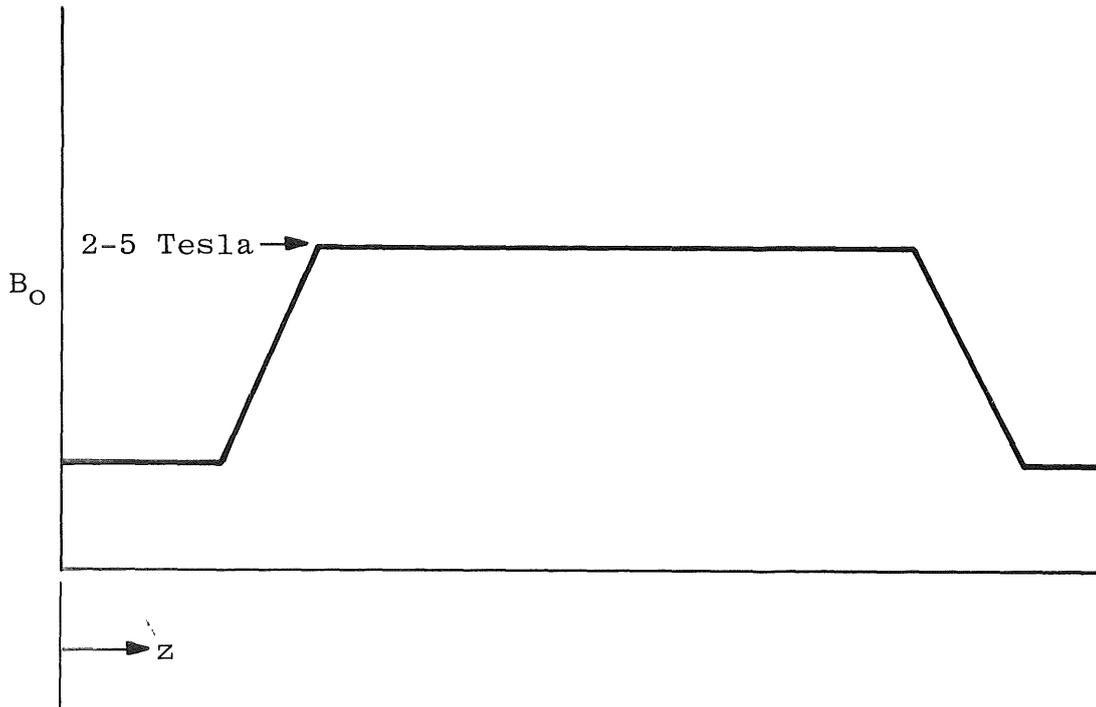
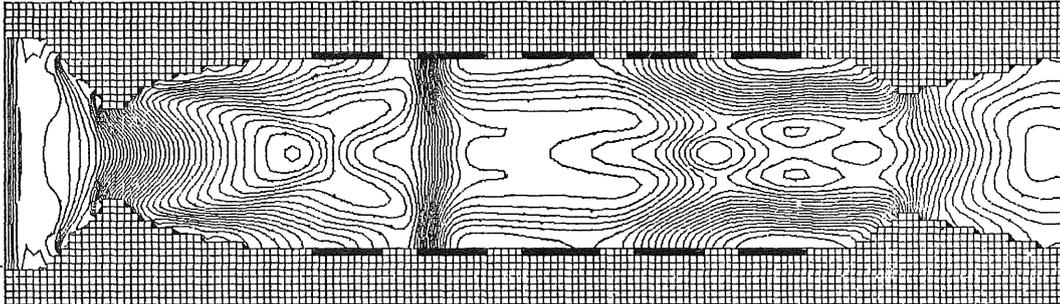


Figure 56 Applied Magnetic Field

TABLE 6. MAGNETOHYDRODYNAMIC GENERATOR CONDITIONS

<u>Thermodynamic Conditions</u>			
Chamber		Ambient	
Pressure	5-10 atm	Pressure	1 atm
Temperature	2500°-3000°K	Temperature	270°K
Density	0.0005 gm/cm ³	Density	0.0013 gm/cm ³
Equation of State:		P = ρ RT	
Specific Heat Ratio:		$\gamma = 1.15$	
Gas Molecular Wt:		MW = 21	

Geometry

Nozzle		Diffuser	
Expansion Ratio:	2	Expansion Ratio:	2
Length:	10 cm	Length:	10 cm
Generator		Electrodes	
Length:	200 cm	Length:	1.0 cm
Height:	20 cm	Height:	0.2 cm
Type:	Faraday	Insulation Thickness:	0.4 cm

(B) An MHD channel containing two electrode-pairs. Start-up is achieved by applying an external magnetic field of strength: 2-5 Teslas and fluxing a gas of constant conductivity: 1-10 Mhos. The creation of current ($\approx \sigma v B$) and subsequently the pondermotive (Lorentz) force $\bar{j} \times \bar{B}$ is examined as a function of time.

(C) An MHD channel containing 8-electrode pairs. The steady state solution of currents, electric fields, ϕ and ψ under inviscid and viscous conditions is studied. The electrical conductivity and Hall parameter are considered functions of thermodynamic state properties and governed by the following relations:

$$\sigma = \frac{\sigma^*}{1+\beta^2} \left(\frac{\rho_{\text{ref}}}{\rho} \right) \left(\frac{T}{T_{\text{ref}}} \right) \quad (215)$$

$$\beta = \frac{B(\text{tesla})}{2} \left(\frac{\rho_{\text{ref}}}{\rho} \right) \quad (216)$$

The viscous boundary layer was assumed turbulent and described by an eddy viscosity model employing the Prandtl mixing length:

$$\tau = \rho \epsilon \frac{\delta u}{\delta y} \quad (217)$$

$$\epsilon = \lambda \frac{2}{E} \left| \frac{\delta u}{\delta y} \right| \quad (218)$$

V. RESULTS OF MHD MODEL

Results of the three cases modeled in Section (4) are now described.

5.1 Case (A): Nozzle-Generator-Diffuser System; Inviscid Conditions

Start-up of a generator, as for a wind-tunnel, consists of a shock moving down the channel and out the diffuser. Figure (57) illustrates a 3-D view of the shock (Mach number) and the current stream function. Figure (58) graphically describes: Mach contours, velocity vectors, ψ contours and current vectors. A three-dimensional view of ψ is shown in Figure (59). Figure (60) illustrates the coupling between gasdynamic and electromagnetic fields. The velocity vectors, current stream function contours and a 3-D view of the current stream function are shown at three time intervals for this three-electrode pair generator. Initially, a shock forms and moves to the exit of the nozzle just preceding the first electrode. An eddy current forms behind this shock (top of figure). As soon as the shock moves into the channel where the first electrode-pair is located, currents form on all three channels and are shorted between electrodes. As the gas flow continues, the currents flow between anode-cathode pairs and the short is eliminated.

5.2 Case (B): MHD Channel; Start-Up

Flow in a simple two-electrode-pair channel (20 cm x 40 cm) was examined when operating with an applied magnetic field turned off and

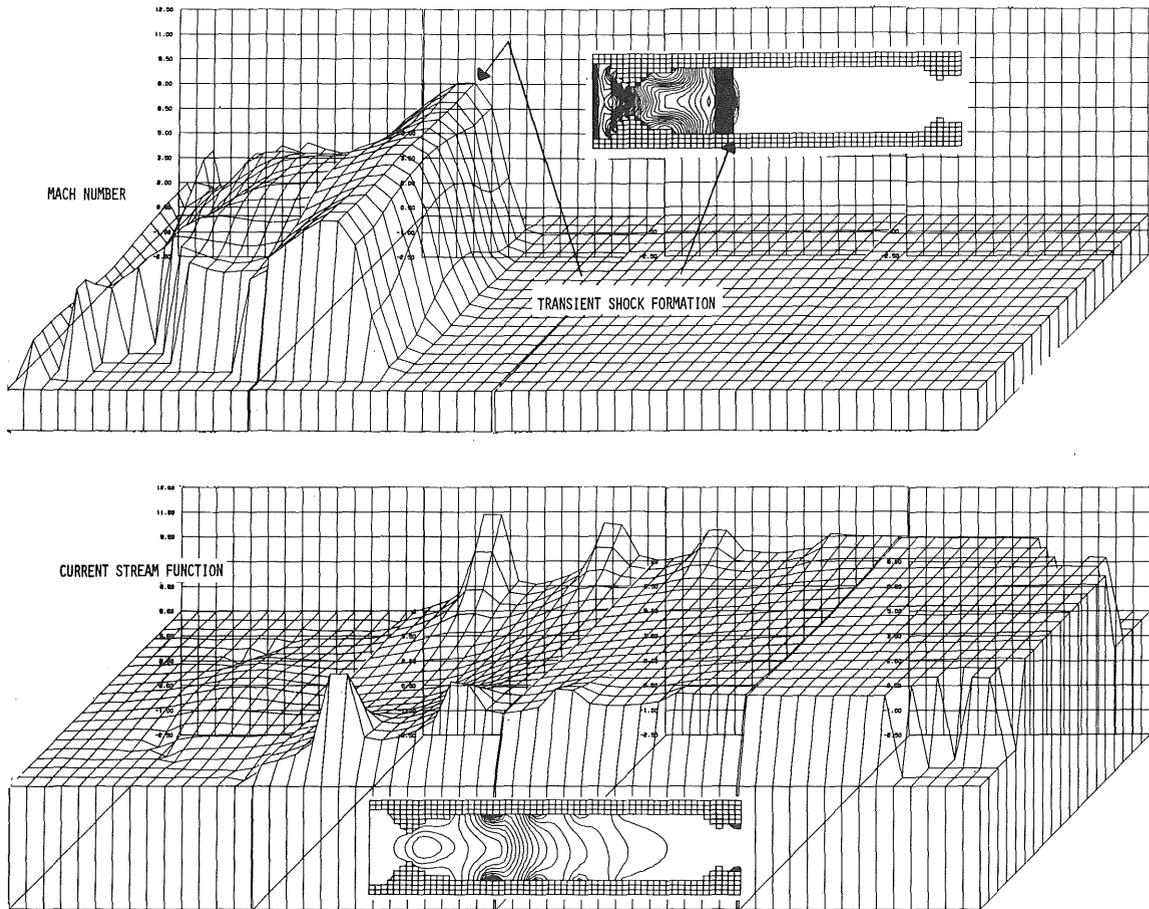


Figure 57 Transient Shock Moving Down a Five-Electrode Pair MHD Generator

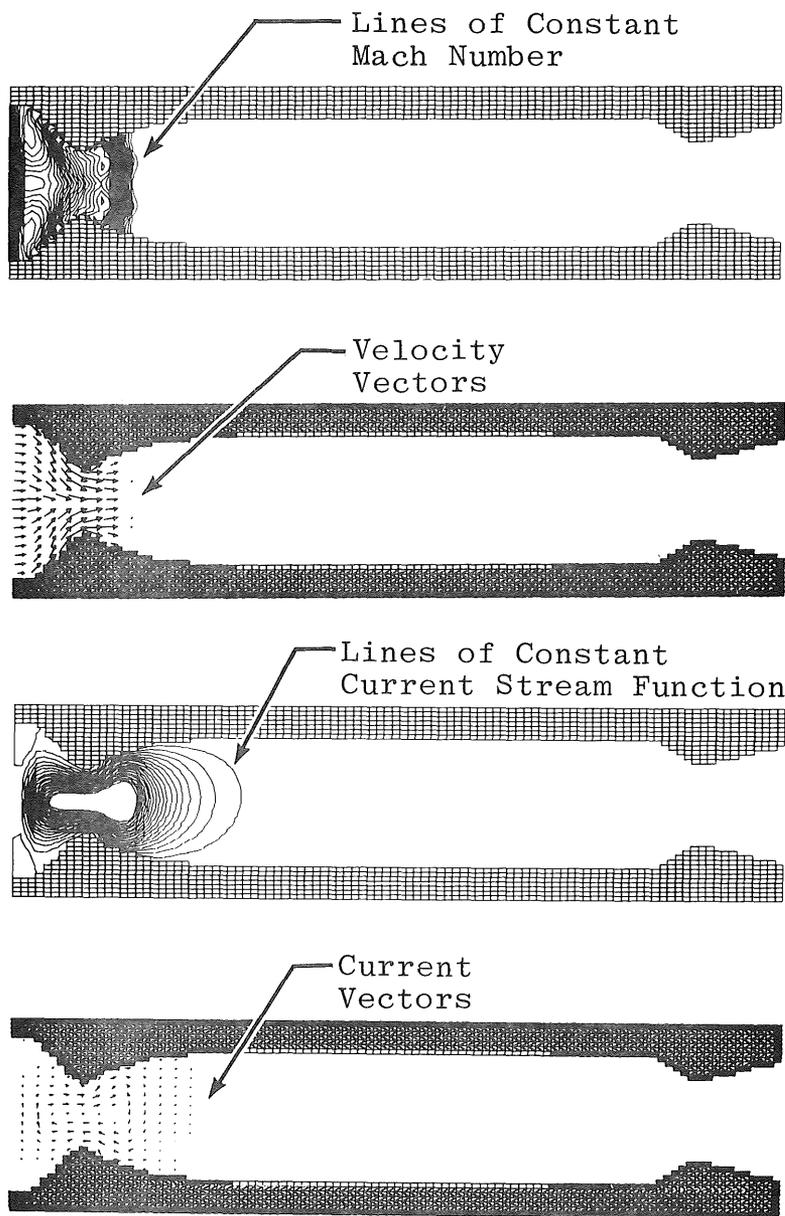


Figure 58 Transient Calculation of a Three-Electrode Pair MHD Generator

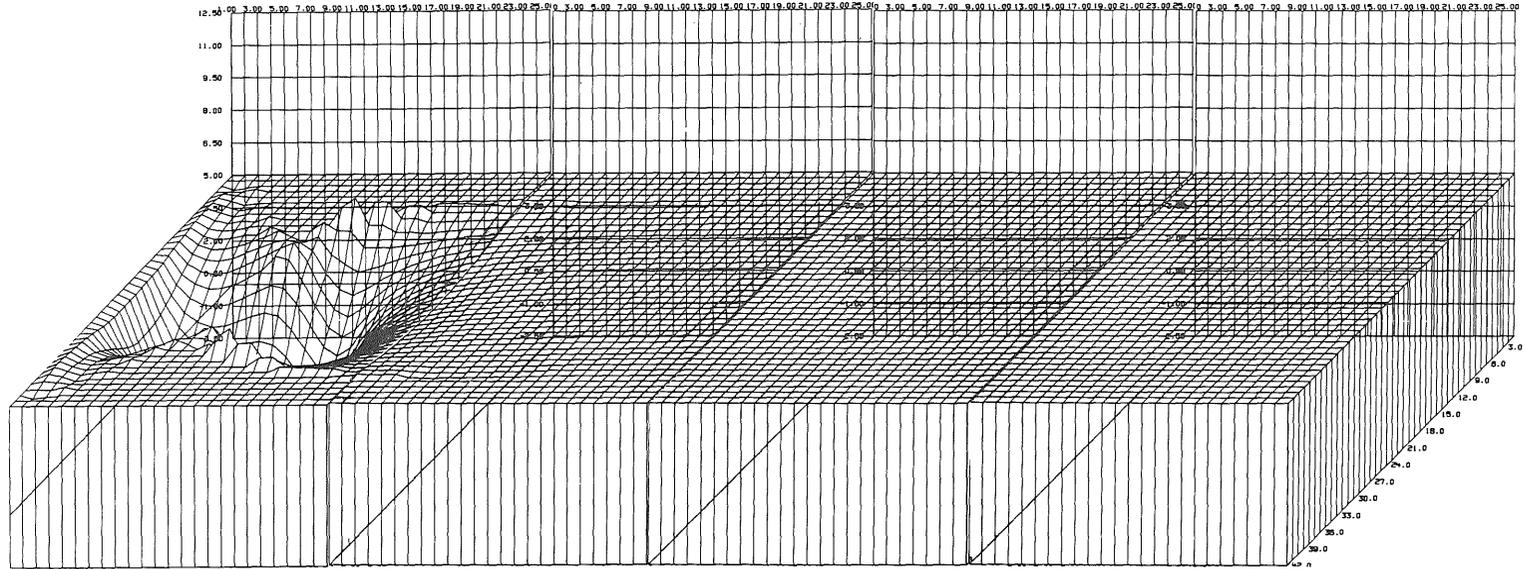


Figure 59 Three-Dimensional View of Current Stream Function for a Three-Electrode Pair MHD Generator

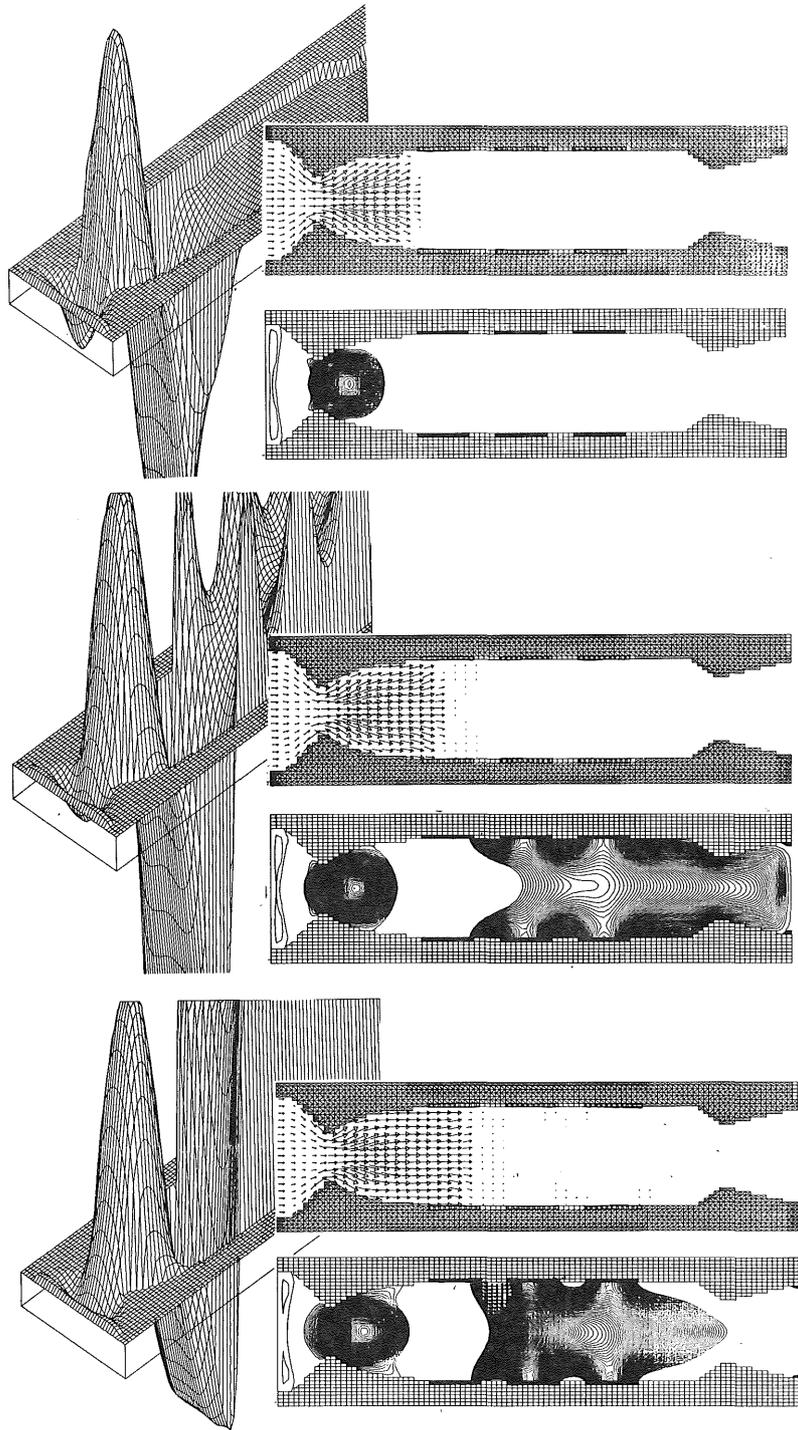


Figure 60 Transient Calculation of Coupled Gasdynamic and Electromagnetic Fields. Velocity Vectors and Current Stream Function (Contours and 3-D View).

then on. Figures (61), (62) and (63) illustrate the results. When the magnetic field is off, the flow reaches an unimpeded steady state velocity of 100,000 cm/sec as would be expected since no dissipative (inviscid, frictionless) forces exist. However, when an external magnetic field of 2 Tesla is applied, the velocity decreases down the channel since the pondermotive force decelerates the flow. The current stream function ψ on the boundary was determined by integrating the current flux across each electrode and recognizing that ψ is constant along an insulator. Initially, the velocity was zero so no net current flowed. As the velocity increased, the current increased. In turn, the current produced an impeding (Lorentz) force to the flow, and the velocity eventually reached equilibrium resulting in a steady state current distribution.

5.3 Case (C): MHD Channel; Turbulence

A channel containing eight electrodes was studied under inviscid and viscous (turbulent) conditions. Figures (64) and (65) contain results for both calculations. Considering the inviscid case, first, the current density (\bar{j}) current stream function (ψ) and electric potential (ϕ) distributions are illustrated in Figures (64) and (65). Employing a turbulent Prandtl mixing length model, the current distributions are perturbed as shown in Figure (65) for one-electrode pair.

Further investigations of the coupling nature between gasdynamic, viscous and electromagnetic forces is a logical extension of the brief results presented here.

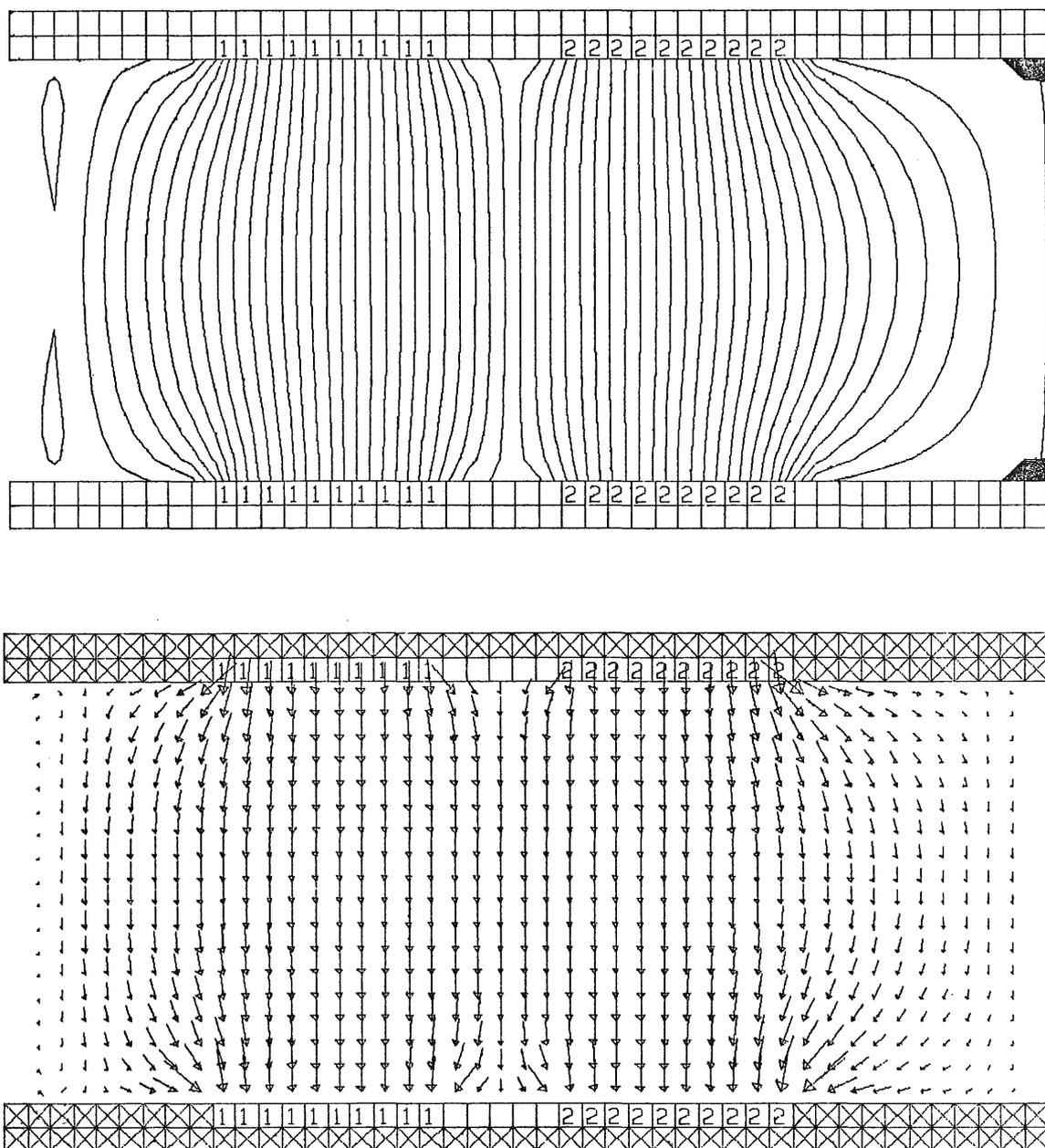


Figure 61 MHD Generator Start Up. Current Stream Function and Current Vectors

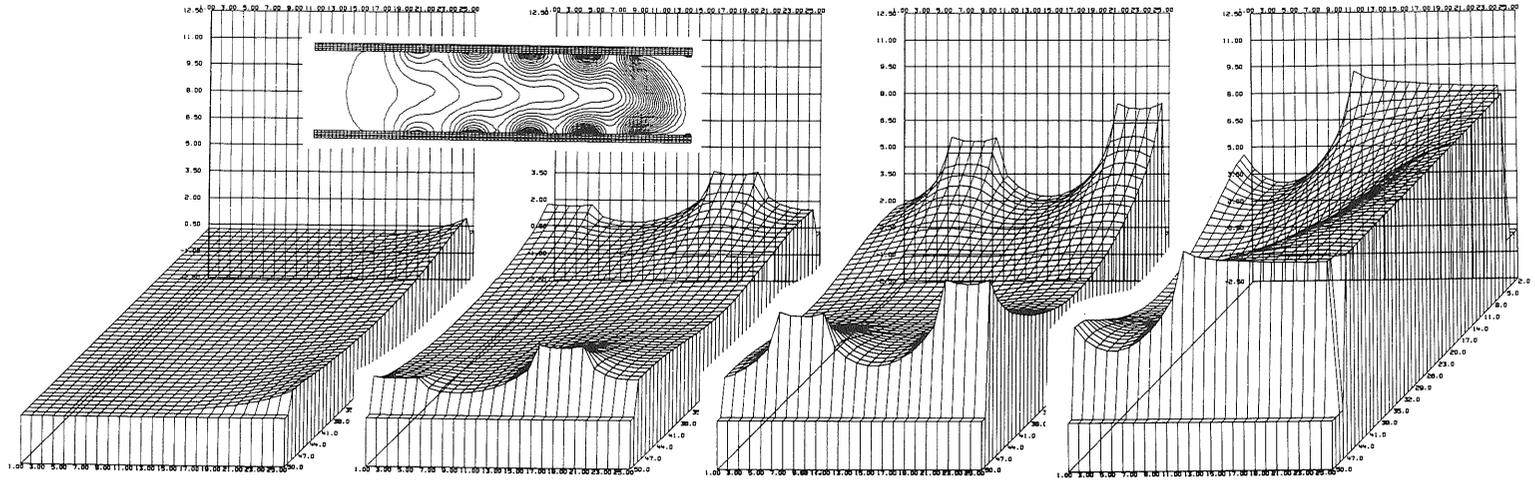


Figure 62 A Three-Dimensional View of the Current Stream Function for a Five-Electrode Pair Channel

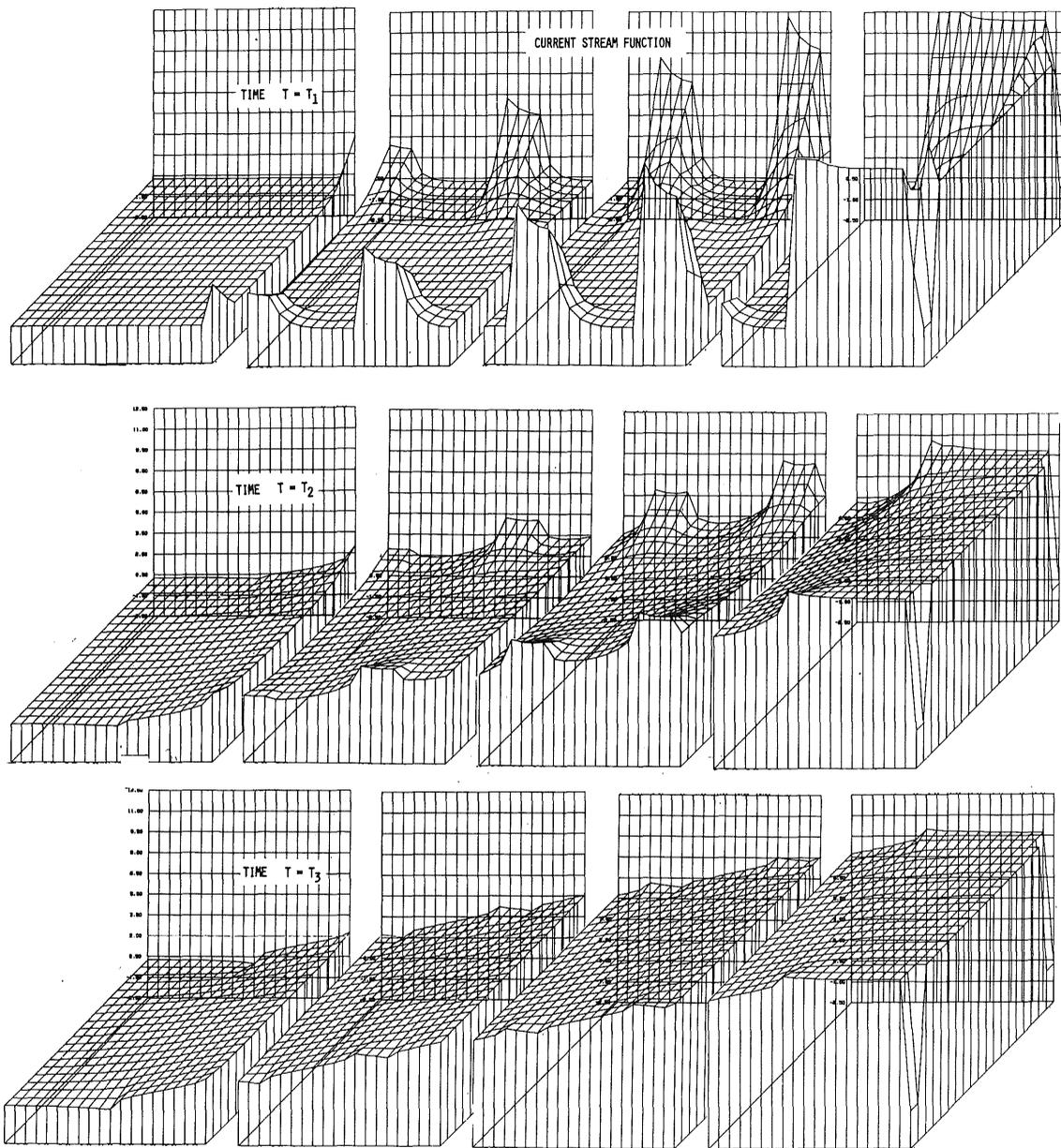


Figure 63 Transient 3-D Views of Current Stream Function for a Five-Electrode Pair Channel.

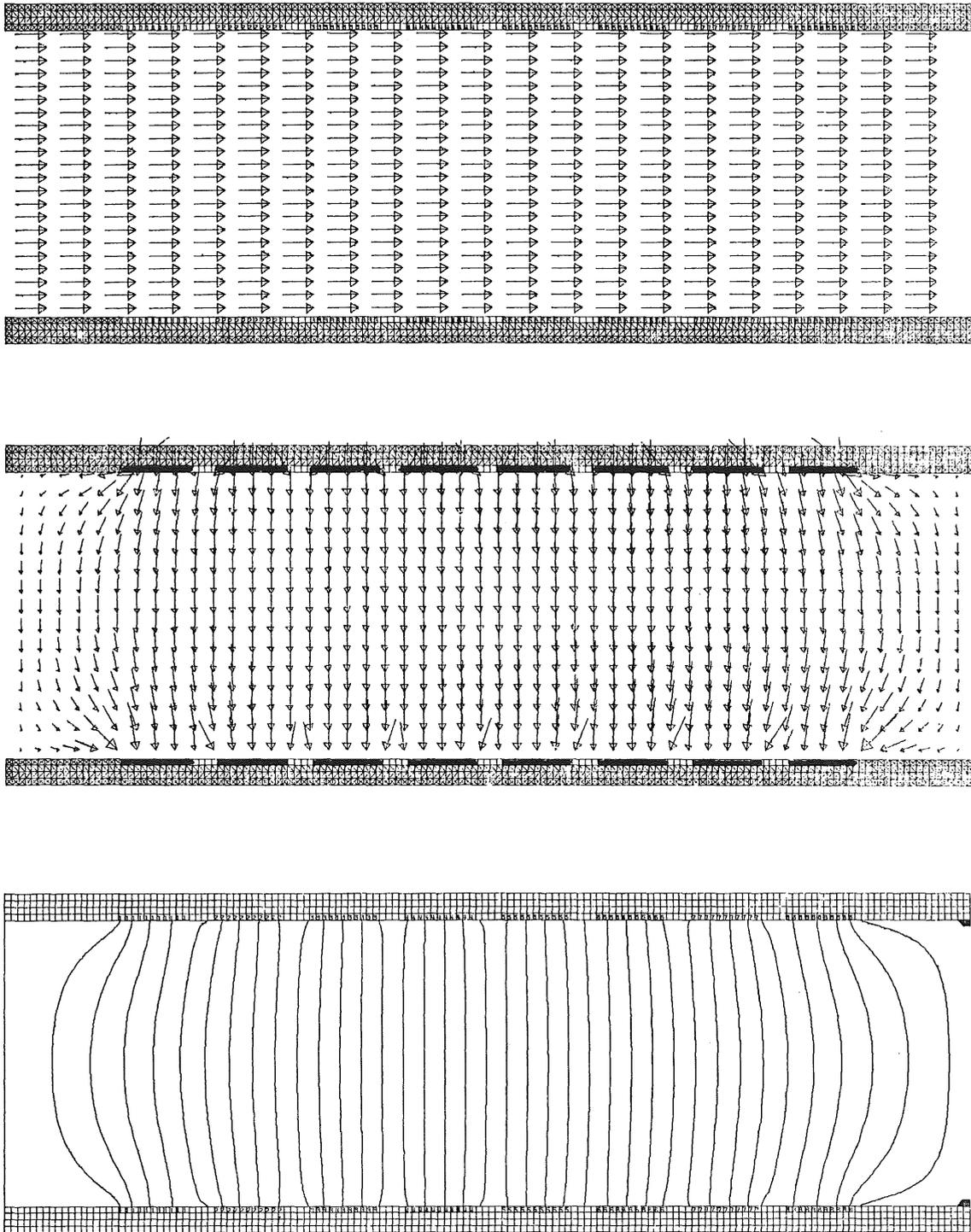


Figure 64 MHD Channel. Current and Inviscid Flow Field Distributions.

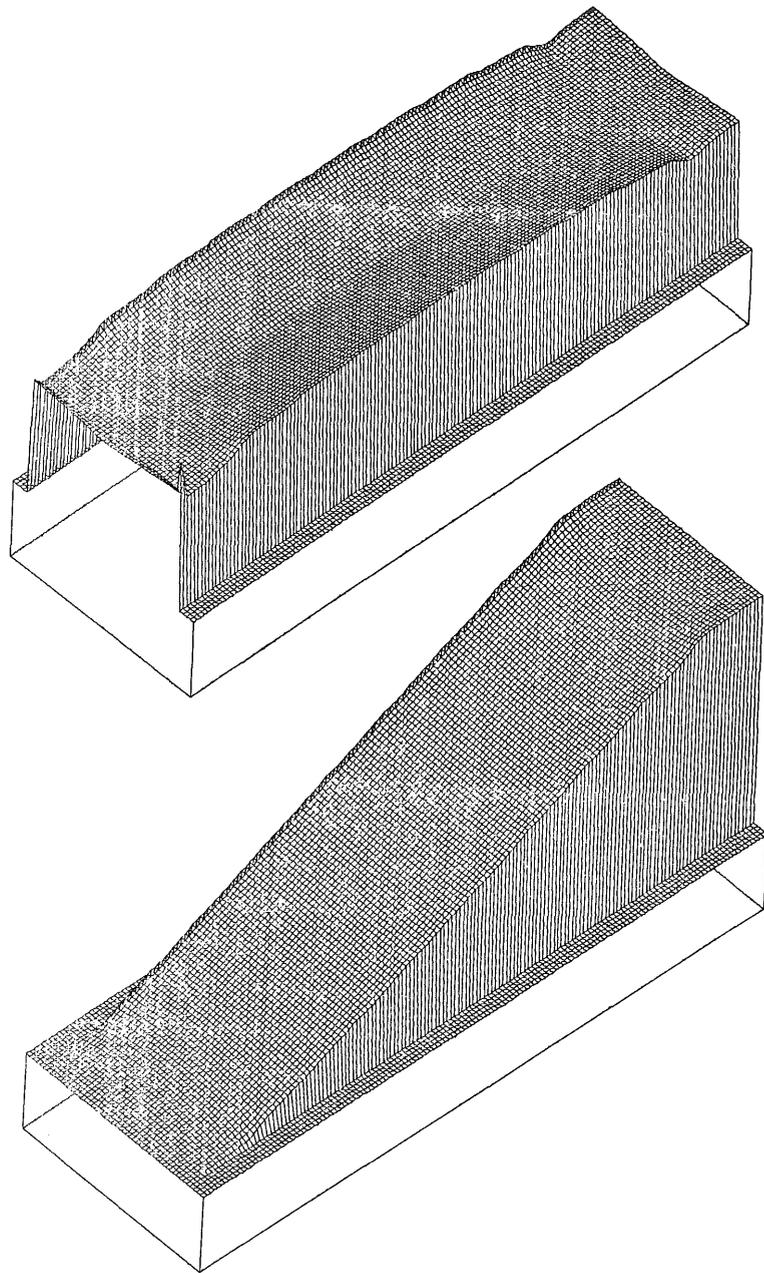


Figure 64 (Continued) Three-Dimensional Views of the Electric Potential and Current Stream Function

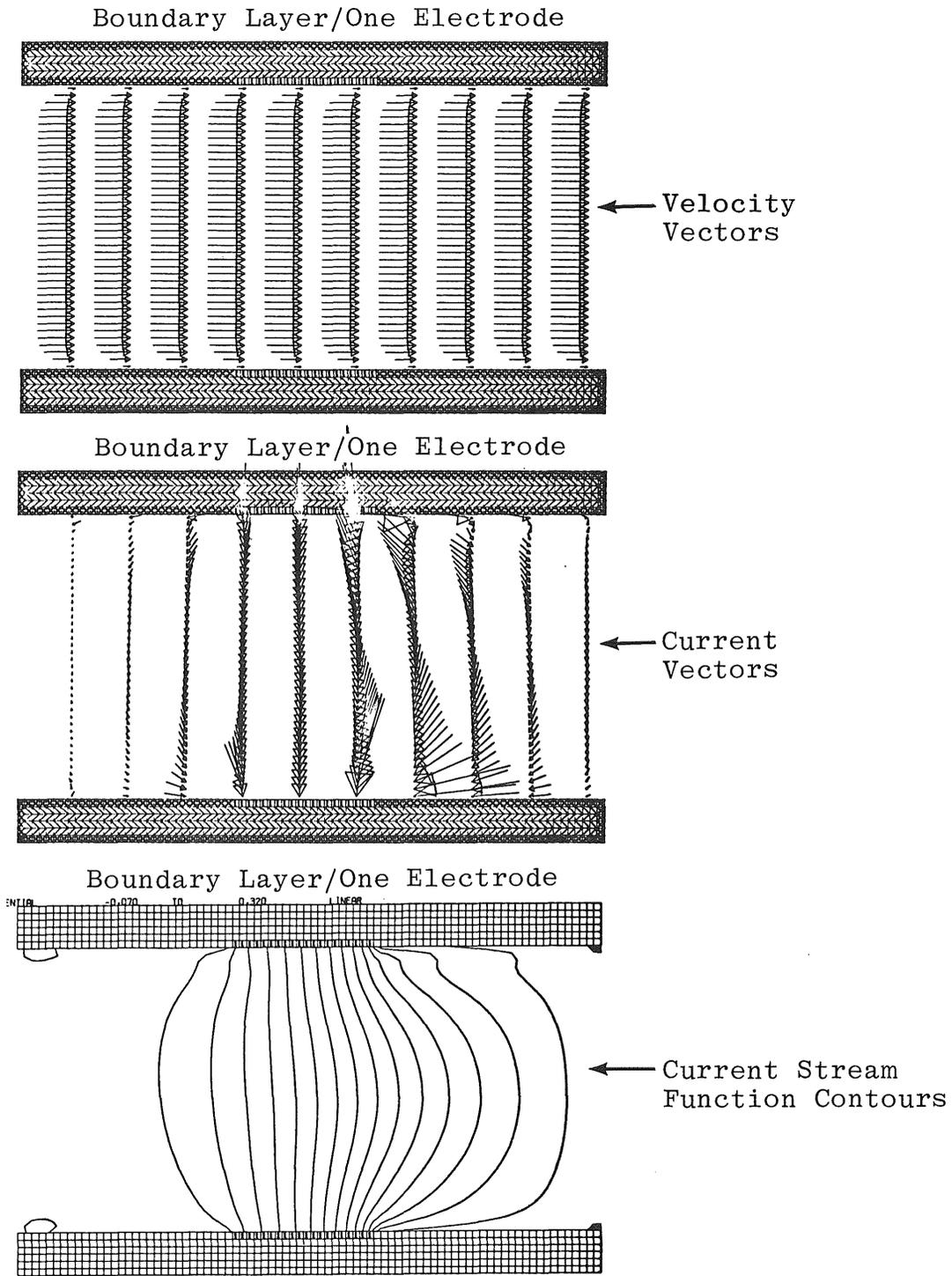


Figure 65 Influence of Boundary Layer on Current Distribution

VI. CONCLUDING REMARKS

6.1 Notes on the Code

Limitations to the numerical procedure discussed in this dissertation can be categorized into the following eight groups:

Computer Time

The primary disadvantage in employing a finite difference technique to the types of problems concerning engineers and physicists is computer time or computational speed. Where other methods arrive at solutions rapidly, this technique may require hours or even days. A two-dimensional transient problem has three coordinates: two spatial and one temporal. Given a mesh of approximately 100 cells in each direction and a calculation performed over approximately 1000 time iterations (cycles) results in $100 \times 100 \times 1000 =$ ten million cell-cycle solutions to the conservation of mass, momentum (r and z), energy, magnetic induction or elliptic equations. Since standard explicit finite difference routines compute on a CDC 6600 at a rate in excess of 1 millisecond per cell per cycle, a typical inviscid, non-MHD transient problem will require 10,000 seconds or two or three hours of central processor time.

However, it has been found that many problems do not require the resolution (10,000 cells) as depicted above nor must they necessarily be carried through to 1,000 time steps. Two-dimensional problems presented in this report range from as low as one minute to as much as three to four hours of CDC 6600 CPU time, depending on geometry,

boundary conditions, particle velocity and the inclusion or exclusion of viscosity, magnetic and/or electric fields. A three-dimensional transient problem would require from 30 minutes to 200 hours. With the inception of faster computers, the CDC computational times may be reduced by a factor of 5, 10 or even 50.

Since the advantages of finite difference techniques are quite evident in that they allow for a complete, reasonably unrestricted solution to the governing conservation equations, it would be only reasonable to expect some price to pay in return. If one, on the other hand takes into account the diversity of problems that can be solved by just this one procedure, as opposed to using numerous other methods or approaches, each restrictive in their very nature, the CP time requirements becomes a less significant handicap.

Inaccurate Material Properties:

Problems solved in this report all assumed a gas which could be characterized as obeying the perfect gas law, or represented by an equation of state which nearly describes this ideal fluid. Since, hydrodynamically, pressure is related to energy and density through this equation of state, a complete breakdown in accuracy occurs when the equation of state is unreliable. Similarly, a poor viscous model (real or eddy coefficient of viscosity) masks the influence of the viscous stress tensor resulting in a distorted boundary layer and adjacent inviscid flow field. The electric and magnetic fields are significantly influenced by the electrical conductivity. Severe error develops when the conductivity is unreliable. Other material properties perturb the flow field similarly.

Unrefined Grid:

Depending on the nature of the problem as dictated by the geometry and boundary conditions disturbing the flow, zone resolution may be so demanding; i.e., 10,000, 50,000, 100,000 cells, etc., that a coarse mesh (employing less cells) may not accurately reflect true hydrodynamic or viscous behavior because of discretization errors (first order truncation errors related to the cell size). In particular, a properly computed boundary layer may require from ten to twenty cells across its thickness in order for energy and momentum contributions to the entire flow field be accurately determined. However, in order to avoid large ratios in the cell size (a square cell yields a minimum truncation error, whereas a rectangle of aspect ratio > 2.5 may result in numerical distortion) the remaining inviscid flow field must be divided into cells of the same order as in the boundary layer; thus, a fully viscous 2-D calculation may require a grid resolution necessitating excessive computer time.

Boundary Conditions:

Unknown or poorly defined boundary conditions results in a costly trial and error procedure where the solution corresponding to a prescribed boundary condition may not be representative of the actual physical problem at hand. Further, a commonly employed uniform flow boundary condition may occur so far from the region of disturbance that the grid resolution becomes unwieldy.

Three-Dimensional Effects:

Unless a problem is planar or 2-D axisymmetric, variations in flow properties in the third dimension may render a 2-D solution meaningless.

Continuum:

The primary assumption of this finite difference technique is that the medium may be treated as a continuum and flow properties over a finite discrete cell do not vary significantly. However, when the mean free path of the fluid particle is not many orders of magnitude less than a cell dimension, as in a rarefied gas, the numerical integration of the conservation equations cannot be accomplished by the method discussed in this report.

Species Composition:*

Only one species was assumed for calculations performed in this study and thus only one equation of state was used. Considering numerous chemical species would require further significant code development and added complexity in tracking each species.

High Reynolds Number (Viscous Flow):

The boundary layer thickness δ is related to the characteristic body dimension by the Reynolds number. For a flat plate, Blasius computed δ to be approximately $5x/\text{SQRT}(\text{Re}_x)$ where x is the distance along the plate, δ/x is thus inversely proportional to the square root of the Reynolds number. For large Re ($> 10^4$) δ/x is small and creates the grid resolution problem of requiring $5/\text{SQRT}(\text{Re}_x)$ axial cells for every radial cell (if square cells are employed). If a grid having cells of

*Species in this case means one material and not one chemical element or molecule.

large aspect ratio is used, numerical distortion may be encountered. At critical Reynolds numbers, viscous instability occurs and a turbulent model must be used.

6.2 Summary and Conclusions

A numerical finite difference technique was developed to treat a wide variety of problems encompassing the disciplines of aerodynamics, gas dynamics, heat transfer, energy conversion and magnetohydrodynamics. Results of the numerous problems attempted and presented in Sections (3) and (5) reveal that this method has proven to be stable and accurate for a number of interesting applications. Major difficulties were encountered when problems such as the re-entry vehicle or MHD generator required more than 10,000 cells in order to preserve numerical accuracy. Computer time became significant in these cases and made numerical experimentation difficult, if not impossible. Boundary layers always presented a severe test to limiting the grid to less than 10,000 cells because the viscous region was usually at least an order of magnitude less than the inviscid region and the approach of varying the cell size through both regions created a significant risk of numerical distortion. Consideration was given to redefining the grid system based on dimensionless geometric, viscous and gas dynamic parameters, such as done by Spalding and Patankar (Ref. 14), but this approach was considered beyond the scope of this effort.

The versatility of this program was demonstrated by treating all Mach regimes: transient and steady state; viscous or inviscid; electromagnetic effects with or without Hall current and nonlinear

material property values. The computation did not decide, a priori, the particular regime or region in which it was calculating, but rather the phenomena were computed as they naturally developed as governed by physical laws which dictated their behavior.

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APPENDIX A
PAST WORK

The predecessor to the hydrocode developed in this dissertation was the HULL hydrodynamics computer code. The objectives and chronological history of HULL as reported in Reference 13 will be briefly outlined below.

The HULL code is a development of the Air Force Weapons Laboratory (AFWL), Kirtland AFB, New Mexico for the theoretical investigation of hydrodynamic phenomena of interest to the USAF. The principal architect of the sophisticated computer logic was Richard E. Durrett. The calculations represent numerical solutions to the inviscid, non-conducting equations of mass, momentum and energy conservation and are performed in an explicit time scheme in an Eulerian reference coordinate system. In order to maintain numerical stability, especially in regions of severe velocity gradients, calculations were performed in two phases, the first, computing a second order accurate Lagrangian integration and the second, fluxing mass, momentum and energy in order to retain the initial grid position; this fluxing procedure is tantamount to re-zoning.

Although the latest version of HULL is vastly superior to the abridged version developed for this research, only the 2-D numerical technique for a single material perfect gas was used. The complex HULL architecture and sophisticated operating philosophy was not employed. HULL is written in higher-level language and generates Control Data Corporation extended Fortran and assembly language routines. The HULL code in its 97th version treats multi-materials, three equations of state, equilibrium radiation diffusion and strength.

The evolution of HULL began in 1955 with the development of PIC (Particle In Cell) by Harlow. In the 1960's, W. E. Johnson authored an Eulerian version of SHELL which employed the two phase scheme of PIC. However, Phase I was numerically unstable until Matuska, in 1970, time and space centered calculations and thus evolved the HULL technique.

The conservation of mass, momentum and energy (Equations (A.1) through (A.4) supplemented with an equation of state are solved by a fully first-order accurate method developed by Matuska:

$$\frac{\delta}{\delta t}(\rho) + \nabla \cdot (\rho \vec{v}) = 0 \quad (\text{A.1})$$

$$\rho \frac{d}{dt}(\vec{v}) = -\nabla p + \rho \vec{g} \quad (\text{A.2})$$

$$\rho \frac{d}{dt}(e) = -\nabla \cdot (p\vec{v}) + \rho \vec{v} \cdot \vec{g} \quad (\text{A.3})$$

$$i = (p, \rho) \quad (\text{A.4})$$

Equations (A.2) and (A.3) are solved in phase I for \vec{v} and e ($\gamma =$ constant). The integration is time and space centered which is vital to the stability of this computation. If the cell size is square and constant throughout the mesh, the solution of these equations will complete a first-order accurate Lagrangian calculation. Equation (A.1) is solved in phase II based on the updated values of e and \vec{v} in phase I. The original coordinates are displaced by an amount equal to the velocity x time step. Next, by computing an appropriate amount of mass that is to be transported from cell to cell, the displaced coordinates are returned to their original positions. In addition to the mass

transported, an amount of momentum and energy is carried along analogous to the convection processes of mass, momentum and energy (see Figure (7)). This is the classical donor cell differencing technique.

Redefining the coordinates to their original values, a somewhat less than rigid interpretation of the difference in Lagrangian and Eulerian derivatives would relate the convective terms in the Eulerian derivatives to the amount of fluxing. For example if the new coordinate points were not arbitrarily restored to their original values, then the amount of fluxing would differ from the convective terms appearing in Equation (A.1) through (A.3) Lindemuth (95) discussed the problems of a fixed or Eulerian space mesh where the convective terms are difficult to center in space and time in the explicit calculation and lead to instabilities or fictitious second order diffusion terms also pointed out by Richtmyer (3). The fluxing procedure described above avoids these two major shortcomings which are inherent in other Eulerian codes. Lindemuth further states the alternative of using a Lagrangian mesh but points out the awkwardness (instability) of the calculation as the mesh becomes greatly distorted. By proper rezoning of this mesh and conserving mass, momentum and energy, the calculation may remain stable. There are methods which retain their distinctive Lagrangian nature by not necessarily rezoning back to the original Eulerian coordinate system; they, however, may suffer either from non-conservation of mass, momentum and

energy or generation of significant non-physical internal energy (and subsequent diminishing kinetic energy) destroying the true physical conditions of the problem.

In performing the fluxing across cell boundaries, mass momentum and total energy are conserved. By examination of Equations (A.1) to (A.3), it is impossible to conserve the quantities of mass, momentum total energy and kinetic energy simultaneously. Kinetic energy is artificially dissipated representing a source of entropy production, especially in regions of large velocity gradients such as near shocks. This implicit viscous dissipation is inherent in all numerical schemes although other programs contain it in the form of an explicit artificial viscosity second order derivative.

As outlined in Section (1), the integration of time derivatives of the fluid properties density, velocity and energy, is performed in two phases. The Lagrangian derivative " d/dT " is computed in phase I; the convective or advective terms are computed in phase II; and the combination of both phases results in a first order accurate Eulerian integration. Space and time derivatives employ central differencing, whereas with time marching in the forward direction.*

Consider the fluid properties known at cycle (n), the method for updating these fluid property values at cycle (n+1) is summarized as follows: At some time $t(n)$ and at cell (i,j), density, radial and axial velocity and energy are known throughout the entire grid. At a

*Time variation of the electric and magnetic fields as well as thermal diffusion (all not included in HULL) is computed between phase I and II and employs the updated velocities and energy computed in the first phase.

later time $t(n+1)$, where $t(n+1) = t(n) + \Delta t$ (see Section (1.3)), the new values of the fluid properties are to be computed.

In order to time and space center calculations, values at the cell interfaces, such as pressure, density and velocity, are computed at $t+\Delta t/2$ ($t(n+1/2)$) and used in the Lagrangian integration. Employing i' and j' indices to indicate new coordinate positions resulting from the Lagrangian integration, the axial and radial velocity and the internal energy are computed at $(n+1)$ based on values of $p, \rho, u, v, (\bar{j}, B)$ and e predicted at cell interfaces.

The next step in the Lagrangian scheme would normally be that of transporting mesh vertices. However, to maintain an Eulerian integration and thus retain the original mesh configuration, the fluxing of hydrodynamic quantities is performed. This fluxing is tantamount to "rezoning" the displaced coordinates back to their original positions. After fluxing is performed and mass, momentum and energy (and magnetic induction) is convected, the displaced coordinates i', j' are returned to their original positions i, j . The amount of fluxing is determined by the velocities of the donor cells and the time interval over which the fluxing procedure occurs.

In conclusion, the HULL code was developed to treat high explosive detonation and nuclear blast phenomena. The equations and numerical formulation could have then just as easily been applied to the numerous aerodynamic and fluid mechanic problems confronting the aerospace engineer. Since 1965, however, other individuals have performed Eulerian and Lagrangian calculations in this field with varying degrees

of success, depending on the stability and convergence of the method used. It is precisely the unique nature of HULL (two phases: Lagrangian/rezone) which enables this method to treat the most severe flow fields in a stable and accurate manner. Finally the dozen or so individuals who spent many years and tens of thousands of CDC 6600 CPU hours developing the HULL hydrocode bears witness to the fact that development of a procedure for solving the conservation equations is, at best, an evolutionary process encompassing the efforts of many.

APPENDIX B
MATHEMATICAL DERIVATIONS

B.1 Time Rate of Change of Pressure

Employing a perfect gas equation of state, the internal energy, conservation of mass and rate of change of internal energy become:

$$i = \frac{1}{\gamma-1} \frac{p}{\rho} \quad (\text{B.1})$$

$$\frac{\delta}{\delta t}(\rho) = -\rho \nabla \cdot \vec{v} \quad (\text{B.2})$$

$$\rho \frac{\delta}{\delta t}(i) = -p(\nabla \cdot \vec{v}) + \frac{\vec{j} \cdot \vec{j}}{\sigma} - (\bar{\tau} : \nabla \vec{v}) - (\nabla \cdot \bar{q}) \quad (\text{B.3})$$

Differentiating Equation (B.1)

$$(\gamma-1) \frac{\delta}{\delta t}(i) = \frac{1}{\rho} \frac{\delta}{\delta t}(p) - \frac{p}{\rho^2} \frac{\delta}{\delta t}(\rho) \quad (\text{B.4})$$

Substituting Equation (B.4) and (B.2) into (B.3) and collecting terms

$$\frac{\delta}{\delta t}(p) = -\gamma p \nabla \cdot \vec{v} + (\gamma-1) \left[\frac{\vec{j} \cdot \vec{j}}{\sigma} - (\bar{\tau} : \nabla \vec{v}) - (\nabla \cdot \bar{q}) \right] \quad (\text{B.5})$$

which represents the change in pressure as a function of time.

B.2 Electrical Boundary Conditions

The relationships between current and electric fields:

$$j_z = \frac{\sigma}{1+\beta^2} (E_z - \beta E_r) \quad (\text{B.6})$$

$$j_r = \frac{\sigma}{1+\beta^2} (E_r + \beta E_z) \quad (\text{B.7})$$

$$E_z = \frac{j_z + \beta j_r}{\sigma} \quad (\text{B.8})$$

$$E_r = \frac{j_r - \beta j_z}{\sigma} \quad (\text{B.9})$$

is derived by expanding

$$\vec{j} = \sigma (\bar{E} + \vec{v} \times \vec{B}) - \frac{\beta}{B} (\vec{j} \times \vec{B}) \quad (\text{B.10})$$

The electrical field components are measured in a coordinate system moving with a velocity v .

Boundary conditions for a multi-electrode system in terms of either ϕ or ψ follows (Fig. 66). Ideal electrodes ($\bar{E}=0$) and insulators ($\bar{j}=0$) are assumed.

Stream Current Function Boundary Conditions

For a stream function ψ

$$j_z = \frac{\delta}{\delta r}(\psi) \quad j_r = -\frac{\delta}{\delta z}(\psi) \quad (\text{B.11})$$

(A) conductors: $E_z=0$

$$j_z + \beta j_r = 0 \quad (\text{B.12})$$

$$\frac{\delta}{\delta r}(\psi) = \beta \frac{\delta}{\delta z}(\psi) \quad (\text{B.13})$$

(B) insulators: $j_r = 0$

$$\frac{\delta}{\delta z}(\psi) = 0 \quad (\text{B.14})$$

or $\psi = \text{constant}$.

Referring to Figure (66)

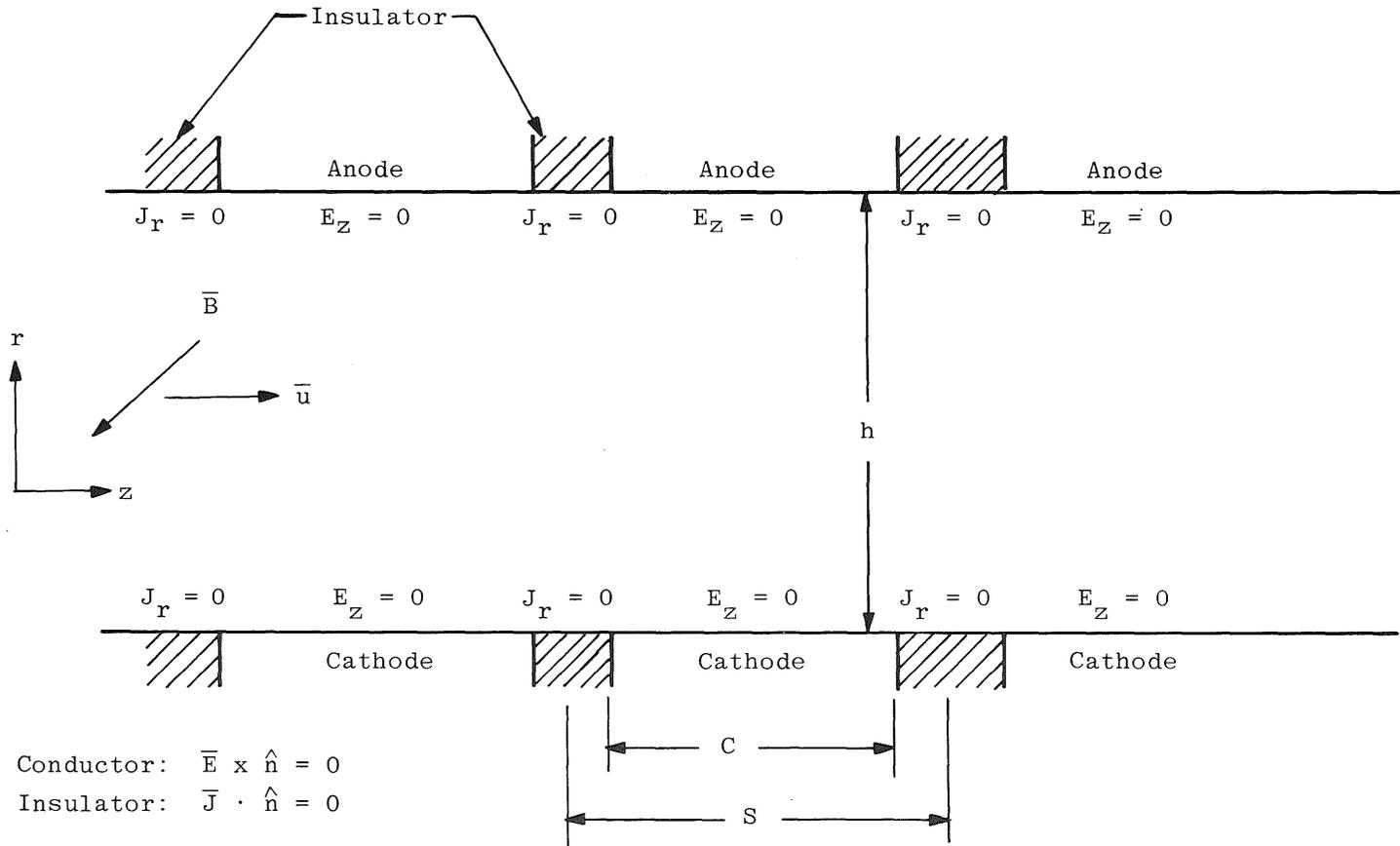
$$\psi_2 = \psi_1 + \frac{\delta}{\delta z}(\psi) \Delta z = \psi_1 - j_r \Delta z = \psi_1 + I_r \quad (\text{B.15})$$

where j_r is the net current in the radial direction flowing in the electrode-insulator pair. Similarly,

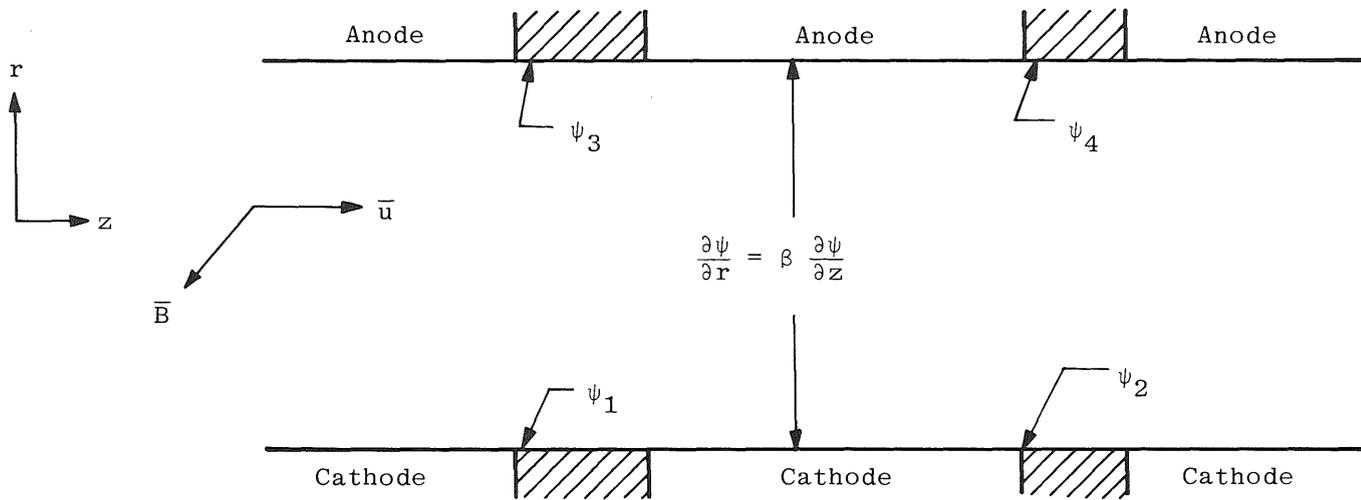
$$\psi_4 = \psi_3 + I_r \quad (\text{B.16})$$

$$\psi_3 = \psi_1 + \frac{\delta}{\delta r}(\psi) \Delta r = \psi_1 + v_z \quad (\text{B.17})$$

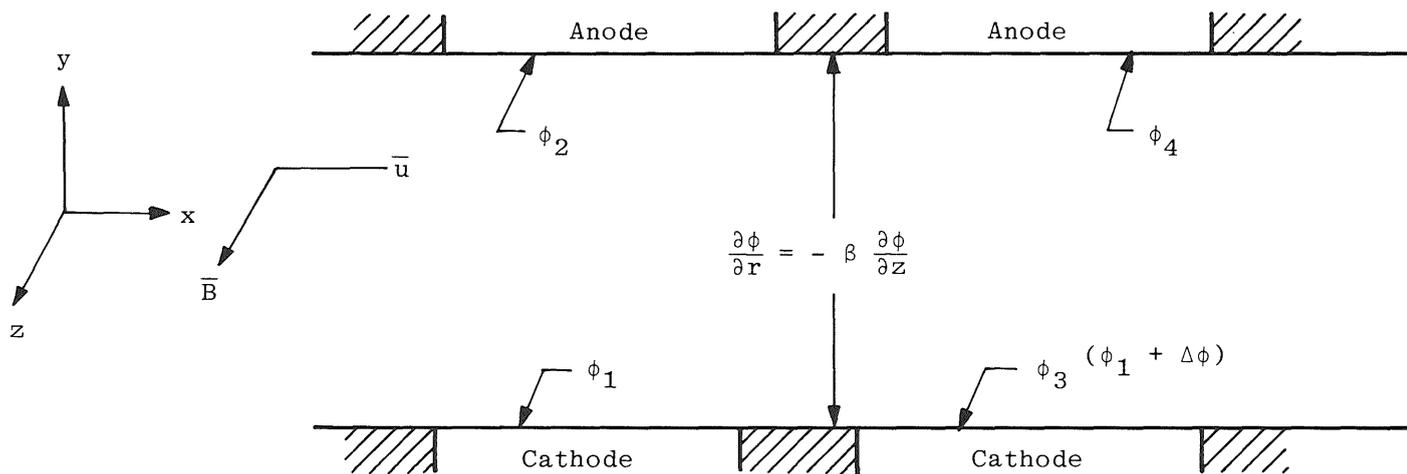
$$\psi_4 = \psi_2 + I_z = \psi_1 + I_r + I_z \quad (\text{B.18})$$



a. MHD Channel
 Fig. 66 Electrical Boundary Conditions



b. ψ Boundary Conditions ($j_z = \frac{\partial \psi}{\partial r}$, $j_r = -\frac{\partial \psi}{\partial z}$)



c. ϕ Boundary Conditions ($E_z = -\frac{\partial \phi}{\partial z}$, $E_r = -\frac{\partial \phi}{\partial r}$)

Fig. 66 (Continued)

Electric Potential Boundary Conditions

$$E_z = -\frac{\delta}{\delta z}(\phi) \quad E_r = -\frac{\delta}{\delta r}(\phi) \quad (\text{B.19})$$

(A) conductors: $E_z = 0$ or $\phi = \text{constant}$

$$\phi_2 = \phi_1 + \frac{\delta}{\delta r}(\phi) \Delta r = \phi_1 - E_r \Delta r = \phi_1 + \Delta\phi_r \quad (\text{B.20})$$

$$\phi_3 = \phi_1 + \frac{\delta}{\delta z}(\phi) \Delta z = \phi_1 + \Delta\phi_z = \phi_1 + V_z \quad (\text{B.21})$$

(B) insulators: $J_r = 0$

$$\frac{\delta}{\delta r}(\phi) = -\beta \frac{\delta}{\delta z}(\phi) \quad (\text{B.22})$$

Thus, for a Faraday generator

$$I_z = 0; \quad \Psi_3 = \Psi_1; \quad \Psi_4 = \Psi_2; \quad \Psi_4 - \Psi_3 = \Psi_2 - \Psi_1 \quad (\text{B.23})$$

equals the net current through the adjacent electrode.

For a Hall generator

$$\phi_3 - \phi_1 = \phi_4 - \phi_2 = V_z; \quad \phi_2 - \phi_1 = -\phi_3 = \Delta V \quad (\text{B.24})$$

where ΔV equals the voltage drop between the anode and cathode.

APPENDIX C
USER'S MANUAL

APPENDIX C

This appendix discusses the FORTRAN-IV computer program which generated the calculations presented in this report. Included are:

- C.1 Program Flow Chart
- C.2 Description of Program Routines
- C.3 Description of FORTRAN Symbols
- C.4 Discussion of Input, Output and Graphics
- C.5 Test Cases
- C.6 Program Suggestions and Diagnostics
- C.7 Hull Difference Method Minority Report
- C.8 FORTRAN IV Listing

Figure C.1 contains a flow chart of the program. Two overlays are employed, the first containing the numerics and the second, the plotting.

The core requirements are dictated by the size of arrays used in the labeled common block "CARRAY." For a 50 x 150 grid, the IBM-370 central memory requirement is 512K and the CDC 6600 is 260K. Reducing the grid to 30 x 75 reduces the core requirements to approximately 300K and 120K, respectively.

Each overlay is composed of approximately 3000 FORTRAN statements or a total of 3 boxes of cards for the complete source program.

TAPE AND DISK UNITSUNIT

- 5 Card input
- 6 Print output
- 14 Plot data written by subroutine GRAPH and read by subroutine GRID
- 15 Restart tape for dumping variables at cycle n (Subroutine OUTPUT) and reading in later (Subroutine INPUT) to restart at cycle n+1.

C.2 DESCRIPTION OF PROGRAM ROUTINES

This section discusses the routines contained in the computer code. The program consists of the following subroutine and functions:

- MAIN - calls either hydro or plot routines
- DRIVER - hydro exec routine

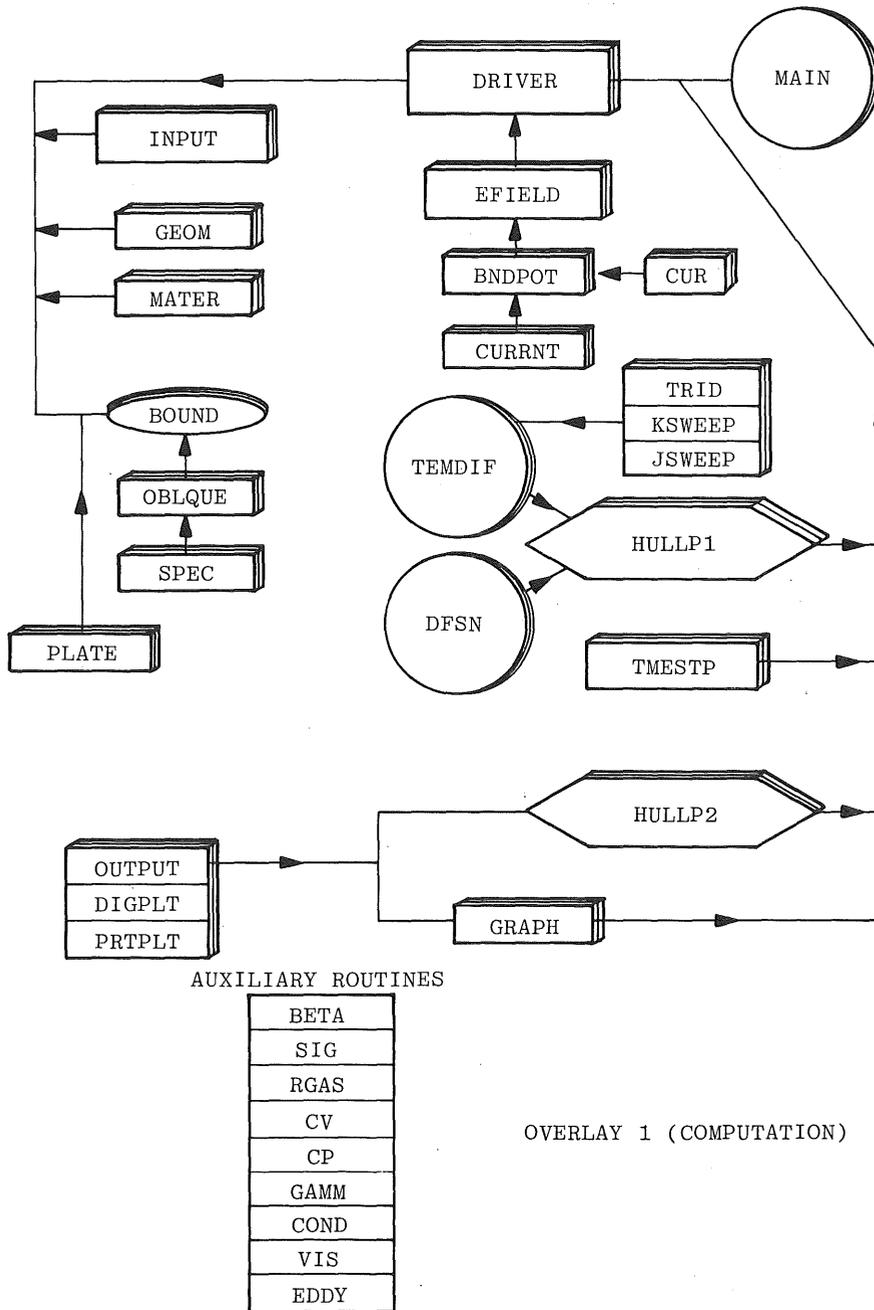


Figure C.1 Flow Chart

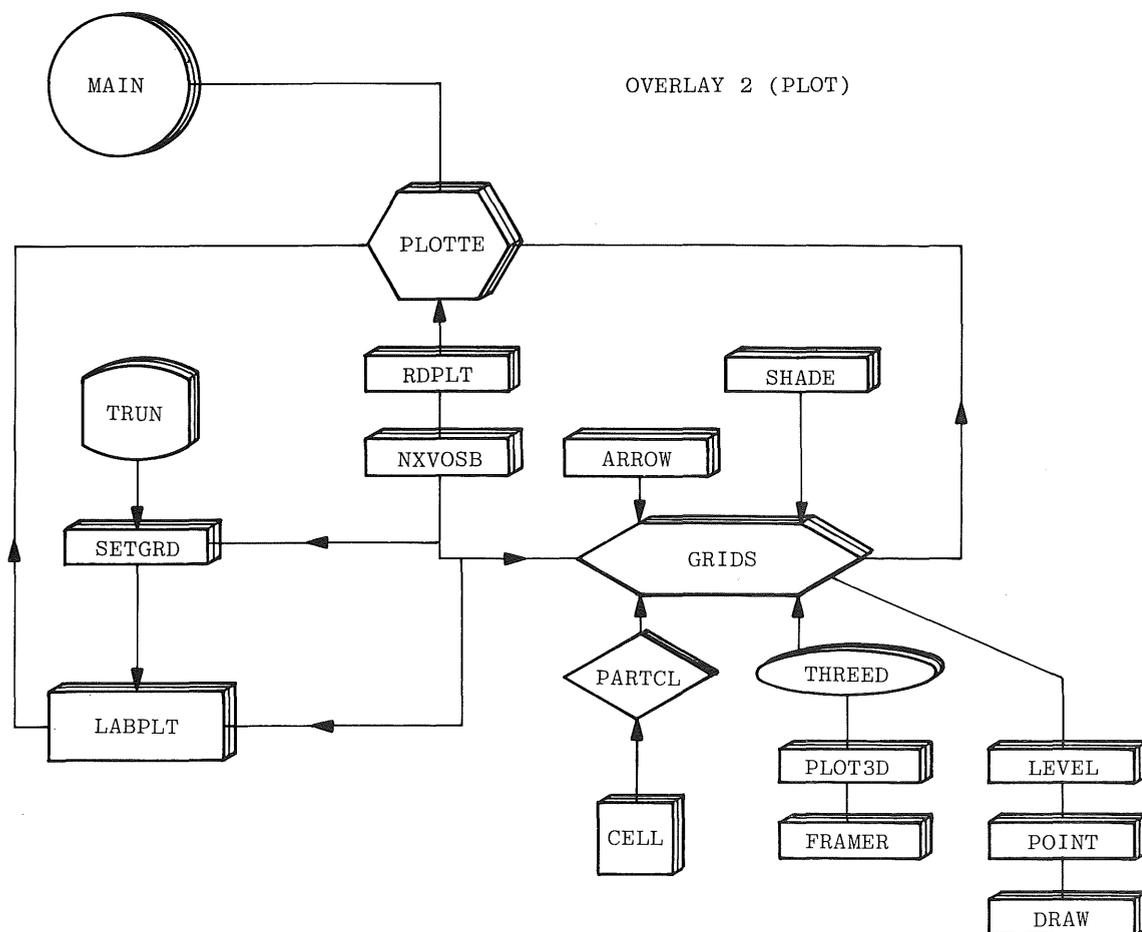


Figure C.1 Continued

INPUT - reads hydro input
GEOM - sets up grid
MATER - defines material properties (presently a dummy routine)
HULLP1 - performs hydro phase I
HULLP2 - performs hydro phase II
TMESTP - computes time step
BOUND - sets up boundary conditions
SPEC - assigns special values to variables and arrays
OBLQUE - determines oblique boundary conditions
EFIELD - performs SOR integration
BNDPOT - defines electrical boundary conditions
PLATE - defines electrode and insulator cells
CURRNT - computes currents and electric fields
CUR - computes radial current entering or leaving each electrode
DFSN - explicit solution of magnetic induction equation
TEMDIF - defines linear matrix for thermal diffusion
KSWEEP - implicit K sweep solution
JSWEEP - implicit J sweep solution
TRID - sets-up tri-diagonal matrix for SOR or ADI
VIS - laminar viscosity function
EDDY - turbulent eddy viscosity function
GAMM - specific heat ratio function
SIG - electrical conductivity function
BETA - Hall parameter
CV - specific heat at constant volume function
CP - specific heat at constant pressure function
RGAS - gas constant function
COND - thermal conductivity function
OUTPUT - writes output
GRAPH - stores plot data
DIGPLT - prints digital plot
PRTPLT - generates digital plot

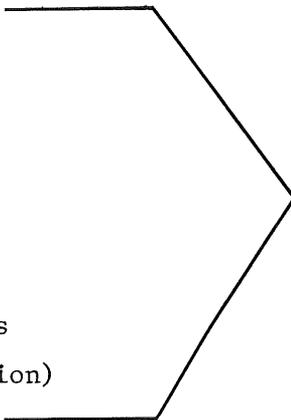
WITH AUXILLARY PLOT ROUTINES:

PLOTTE	- plot exec routine
RDPLT	- reads plot input
SETGRD	- sets up grid axis and labels
LABPLT	- generates time history or spatial distributions
GRIDS	- plots grids
TRUN	- truncates axis coordinate values
SHADE	- shades grids
NXVOSE	- scales plot array
PARTCL	- depicts tracer particles
CELL	- locates cell (I,J) corresponding to a set of coordinates
ARROW	- draws arrows
LEVEL	} - contour plot package
POINT	
DRAW	
THREED	} - three dimensional plot package
PLOT3D	
FRAMER	

PLOT AND AUXILIARY ROUTINES

Stromberg-Carlson 4020

FRAMEV	- advances frame
LINEV	- draws line
PLOTV	- plots symbol
PRINTV	- plots letter
RITSTV	- controls letter spacing
CHSIZV	- controls character size
DXDYV	- scale routine
<u>CALCOMP</u>	
CALCMP	- executes numerous plot commands
PLOT	- moves pen (in up or down position)
LINE	- connects an array of points
SYMBOL	- plots a string of symbols



See
"SIMULATORS"
Page 361

NUMBER - plots a number
 GSIZE - calls for specific pen and paper
 SECOND - gives cp time in seconds
 (CDC 6600)
 TIMER - gives cp time in seconds
 (IBM 370)

1st OVERLAY

Referring to Figure C.1, main calls DRIVER which serves as the executive routine. Initially INPUT, GEOM, and BOUND are called to set up initial and boundary conditions and grid network. DRIVER then calls the hydrodynamic subroutines: HULLP1 (phase I), HULLP2 (phase II), electromagnetic routines, EFIELD, thermal and magnetic diffusion routines: TEMDIF and DFSN, time-step calculation, TMESTP and the output routines: OUTPUT, DIGPLT, PRTPLT, and GRAPH (plot data).

Boundary conditions (BOUND) are defined as fixed, reflective or transmissive for each of the four boundaries. OBLQUE treats the curvature of oblique boundaries intersecting cells. Subroutine SPEC assigns special values to hydrodynamic or electromagnetic every cycle and BNDPOT assigns the electric potential or current stream function to electrodes and insulators. PLATE identifies the anode-cathode pairs.

Subroutine HULLP1 integrates the equations of motion in a Lagrangian reference frame. Subroutine HULLP2 transports mass employing the "donor-receiver" technique. The electromagnetic calculation is performed by EFIELD which solves the elliptic partial differential equation for the electric potential or current stream function. The method of Successive-Over-Relaxation was employed. If the time-dependent magnetic induction equation is solved, DFSN is called. Viscous effects are computed in HULLP1 employing the functions VIS or EDDY describing viscosity. Subroutine TEMDIF solves implicitly, the time-dependent heat conduction term (energy equation) by alternating directions in sweeping the grid: KSWEEP and JSWEEP. Subroutine TRID solves the tri-diagonal matrix formed.

Functions VIS, EDDY, GAMM, SIG, BETA, CV, CP, RGAS and COND compute properties at cell i,j based on the temperature, pressure, etc., at that cell.

2nd OVERLAY

Subroutine PLOTTE calls RDPLT for data input, sets up appropriate arrays for plotting time histories or spatial distributions or call GRIDS for contour, shading or 3-D plots. Subroutine SETGRD sets up the labeled axis. LABPLT draws the curves representing time history or spatial distributions of certain variables. GRIDS draws lines connecting nodal points and sets up data for vector, contour shade, 3-D and particle (tracer) plots.

NXVOSB is a scale routine which determines the location of points to be plotted. TRUN truncates a number to be used in labelling an axis. ARROW draws the head of vectors. PARTCL generates tracer particle and stores the particle trajectory data whereas CELL identifies the location of the tracer particle. Subroutines LEVEL, POINT and DRAW draw contour maps whereas subroutines THREED, PLOT3D and FRAMER construct 3-D plots. PLTMX and PLT3D1 represent an alternate 3-D plot package. The contour plot package was developed by ARO, Inc., Arnold AFS, TN, whereas the 3-D plot packages were developed by the University of Texas and AEDC, Eglin AFB, FL.

C.3 DESCRIPTION OF FORTRAN SYMBOLS

This section contains a list of major FORTRAN symbols other than those to be discussed in the input section (C.4).

BO	- theta magnetic induction
BPRES	- magnetic pressure
BR	- radial magnetic induction
BZ	- axial magnetic induction
CMACH	- Mach number
CMPR	- cell compressive energy
COND	- thermal conductivity
CV	- specific heat at constant volume
DANGLE	- angle of oblique boundary
DELTA	- angle of oblique boundary
DR	- radial dimension of cell
DEVU	- axial velocity change due to deviatoric stress
DEVV	- radial velocity change due to deviatoric stress
DT	- time step
DZ	- axial dimension of cell
E	- energy/unit mass
ER	- radial electric field
EZ	- axial electric field
GR	- radial gravitation (set = 0)
GZ	- axial gravitation (set = 0)
INT	- oblique boundary indicator
IOBK	- oblique boundary indicator

JR	- radial current
JZ	- axial current
NCONV	- convection time counter
NMAGN	- magnetic time counter
NTHRM	- heat conduction time counter
NVISC	- viscous time counter
M	- mass (new)
MLJ	- mass (old)
P	- pressure
PERM	- permeability
PHI	- electric potential
R	- radial position of cell
RIMH	- radial position at $I - 1/2$
RIPH	- radial position at $I + 1/2$
RIP3H	- radial position at $I + 3/2$
RDIST	- radial position of oblique boundary
RGAS	- gas constant
RHO	- density
SIG	- electrical conductivity
SPHU	- axial velocity change due to pressure
SPHV	- radial velocity change due to pressure
T	- time
TEMP	- temperature
THETA	- angle of velocity vector
TOO	- azimuthal stress
TRR	- radial stress
TRZ	- shear
TZZ	- axial stress
U	- axial velocity
V	- radial velocity
VISC	- viscosity
Z	- axial position of cell

C.4 DISCUSSION OF INPUT, OUTPUT, AND GRAPHICS

Card input with FORTRAN symbols and format is defined below. Examples follow later in this report.

INPUT (HYDRO)

UNITS G(GM), C(CM), S(SEC), E(ERG), GA(GAUSS), P(POISE), O(OHM),
M(METER), K(DEG K), A(ATM), D(DYNES), V(VOLTS), AC(ABCOULOMB)

CARD ONE (15A4)

TITLE 1-60 TITLE IDENTIFICATION -

CARD TWO (1615)

KMAX	1- 5	number of cells in radial direction		-
JMAX	6-10	number of cells in axial direction		-
IAXI	11-15	(0) cartesian, (1) cylindrical coordinates		-
IPTSF	16-20	(1) current stream function, (2) electric potential		-
ISYM(1)	21-25	boundary conditions (0) fixed		-
ISYM(2)	26-30	(1) transmissive, (-1) reflective	2	-
ISYM(3)	31-35	for bottom, left, top, right boundaries	1	-
ISYM(4)	36-40			-
NVECT	41-45	(0) no oblique boundary, (1) top oblique, (2) top and bottom oblique		-
NPDIM	46-50	(0) no plot tape, (1) plot tape		-
MCALC*	51-55	type calculation: (viscous, EMF)		-
IRST**	56-60	(-1) write restart tape, (+1) read restart tape		-
IOBQ	61-65	(0) no obliq bdry, (+1) oblq bdry, (-1) no slip		-
IPOT	66-70	(0) no emf, (N) every Nth cycle, the potential or stream function is solved for.		-

*The program was designed to eliminate the viscous or electromagnetic logic by selecting MCALC accordingly:

0	INVISCID	}	
1	LAMINAR		
2	TURBULENT		
3	INVISCID	}	MAGNETIC
4	LAMINAR		INDUCTION
5	TURBULENT		

6 INVISCID	}	ELECTRIC POTENTIAL
7 LAMINAR		OR
8 TURBULENT		CURRENT STREAM FUNCTION

A viscous or magneto-stress calculation takes roughly twice as much CP time per cycle as a simple inviscid problem. Solving the electric potential or stream current function may take even considerably more time.

The "restart" capability is a means in which long executing jobs may be run in segments. As an example, given a 4-hour job which is to be run in 8 - 1/2 hour segments. Initially, IRST is set = "-1" and the program is run NMAX cycles. At the end of the run ($NPRN \leq NMAX$) a tape on unit 15 writes all appropriate information in order that the calculations may continue later. In the next segment, IRST is set = "1" and the same card input along with the restart tape (unit 15) initiates the next sequence of calculations. After this calculation is completed, a new "dump" on tape 15 is performed and further calculations proceed in the same manner. No changes are required to the deck after IRST is set = 1 and the deck can be read in repeatedly in 1/2 hr, 1 hr, etc., segments.

IF IOBQ \neq 0 READ CARD THREE A:

CARD THREE A

RD	1-10	r coordinate of oblique boundary*	C
XD	11-20	z coordinate of oblique boundary	C

IF IPOT \neq 0 READ CARD THREE B:

SPACE	1-10	number of cells per electrode	-
SPINSL	11-20	number of cells per insulator	-
BASEP	21-30	number of EMF integrations on the first cycle	-
DPOT	31-40	number of EMF integrations on the ensuing cycles	-
DVOLT	41-50	dummy	-
JPLMIN	51-55	initial conductor (or insulator) cell	-
JPLMAX	56-60	final conductor (or insulator) cell	-

CARD FOUR (815)

NPRN	1- 5	print interval in cycles	-
KPDEL	6-10	print for every kth cell	-
JPDEL	11-15	print for every jth cell	-
NPLOT	16-20	plot tape interval in cycles	-
NDIGPL	21-25	(0) no digital plot, (1) digital plot	-
NMAX	26-30	terminal cycle	-
NCYCLE	31-35	initial cycle	-

*If electrodes are employed (IPOT \neq 0), at least two boundary cells must be defined.... see Fig. C.9, page 227.

CARD FIVE (8E10.4)

DZØ	1-10	cell spacing in axial direction	C
DRØ	11-20	cell spacing in radial direction	C
ZMIN	21-30	minimum axial location	C
RMIN	31-40	minimum radial location	C
MINDT	41-50	minimum time step	S
MAXDT	51-60	maximum time step	S
STAB	61-70	stability factor	-
TZERO	71-80	initial time	S

CARD SIX (8E10.4)

RHOØ	1-10	density	G/C3
VZ	11-20	axial velocity	C/S
VR	21-30	radial velocity	C/S
EØ	31-40	energy/mass	E/G
BØ	41-50	magnetic induction - theta	G
BRØ	51-60	magnetic induction - R	G
BZØ	61-70	magnetic induction - Z	G

CARD SEVEN (4E10.4)

VISCØ	1-10	viscosity	P
PERMØ	11-20	permeability	-
MW	21-30	molecular weight	-
ARFV	31-40	artificial viscosity (0) off, (1) on	-

CARD EIGHT TO TEN (415,/,7E10.4,/,5E10.4)

K1	1- 5	special assignment of cell variable values	-
J1	6-10	from K1 to K2 in radial direction and J1	-
K2	11-15	to J2 in axial direction	-

J2	16-20		-
BRHO \emptyset	1-10	same variables as defined before, e.g. BE \emptyset and	G/C3
BVZ	11-20	E \emptyset	G/C
BVR	21-30		G/C
BE \emptyset	31-40		E/G
BB \emptyset	41-50		G
BBR \emptyset	51-60		G
BBZ \emptyset	61-70		G
BVISC \emptyset	1-10		P
BPERM \emptyset	11-20		-

REPEAT CARDS 8-10 WITH LAST SET BLANK

INPUT (PLOT)

UNITS G(GM), C(CM), S(SEC), E(ERG), GA(GAUSS), P(POISE), O(OHM),
M(METER), K(DEG K), A(ATM), D(DYNES), V(VOLTS), AC (ABCOULOMB)

CARD ONE (915.5X,E10.4)

MOVIE	1- 5	(0) no movie, (1) 16 or 35 mm movie (3) contour plot	-
IHIST	6-10	number of time history plots	-
ISPAT	11-15	number spatial distribution plots	-
IPARAM	16-20	number of parameter plots	-
ILINE	21-25	number of line elimination cards	-
ISC	26-30	(0) no shading, (-1) shading and/or contour mapping	-
IDET	31-35	(0) labels, (1) no labels, (3) punched cards of shade intensity, (5) 3-D plots	-
ISYM	36-40	(0) no symmetry, (1) mirror image about r-axis, (2) mirror image about z-axis	
IVEL	41-45	(0) no vectors, (1) vectors	
RPV	51-60	vectors plotted at inches/plot variable value	VAR

CARD TWO (1015)

ILOW	1- 5	minimum radial index to be plotted	-
JHIGH	6-10	maximum radial index to be plotted	-
JLOW	11-15	minimum axial index to be plotted	-
JHIGH	16-20	maximum axial index to be plotted	-
L1	21-25	if ILOW.NE.1, JLOW.NE.1, IHIGH.NE.KP2	-
L2	26-30	JHIGH.NE.JP2	-
L3	31-35	L1 = 1, L2 = KP2, L3 = 1, L4 = JP2	-
L4	36-40	otherwise L1 = L2 = L3 = L4 = 0	-
JPDEL	41-45	plot interval in axial direction	-
KPDEL	46-50	plot interval in radial direction	-

CARD THREE (4F10.4)

ZLOW	1-10	minimum axial coordinate	C
ZHIGH	11-20	maximum axial coordinate	C
XLOW	21-30	minimum radial coordinate	C
XHIGH	31-40	maximum radial coordinate	C

CARD FOUR (215)

IVX	1- 5	ordinate variable in vector plot (8 for velocity)	-
IVZ	6-10	abscissa variable in vector plot (7 for velocity)	-

CARD FOUR A (5I5)IF IPART \neq 0 READ:

IPLOW	1- 5	minimum ith particle cell location	-
IPHIGH	6-10	maximum "	-
JPLOW	11-15	minimum jth "	-
JPHIGH	16-20	maximum "	-
NPTS	21-25	number of cycles when new particles originate	-

CARD FIVE (6I5)

IHMIN	1- 5	minimum row for time history plots	-
IHMAX	6-10	maximum row for time history plots	-

JHMIN	11-15	minimum column for time history plots	-
JHMAX	16-20	maximum column for time history plots	-
MCODE	21-25	variable plotted (see table C.1)	-
MFRAME	26-30	number of time history plots per frame	-

CARD SIX (6I5)

ISMIN	1- 5	minimum row for line elimination	-
ISMAX	6-10	maximum row for line elimination	-
JSMIN	11-15	minimum column for line elimination	-
JSMAX	16-20	maximum column for line elimination	-
NCODE	21-25	(1) axial coordinate (horizontal) (2) radial coordinate (vertical)	-

CARD SEVEN (6I5) (At present, these values are overridden in GRIDS)

IZMIN	1- 5	minimum row for spatial distribution plots	-
IZMAX	6-10	maximum row for spatial distribution plots	-
JZMIN	11-15	minimum column for spatial distribution plots	-
JZMAX	16-20	maximum column for spatial distribution plots	-
MZODE	21-25	variable plotted (see table C.1)	-
MFRAME	26-30	number of spatial distribution plots per frame	-

CARD EIGHT (2E10.4,3(5X,I5))

Referring to Table C.1. Each cell (identified by indices I,J) has 36 variables stored on the disk by Subroutine GRAPH. These values are later employed to generate plots. At cycle intervals of NPLT, Subroutine GRAPH writes on disk unit 14. Later, when plotting is performed, Subroutines PLOTTE or GRIDS rewinds disk unit 14 and searches for specific plot data at various times and/or grid locations.

E1	1-10	minimum value to be shaded	VAR
E2	11-20	maximum value to be shaded	VAR
LI1	26-30	variable to be shaded (see table C.1)	-
LI2	36-40	(0) linear shade scale, (1) logarithmic scale	-
LI3	46-50	(0) shade only, (1) shade and velocity vectors	-

CARD NINE (5I5)

ISHIN	1- 5	minimum row to be shaded	-
ISHAX	6-10	maximum row to be shaded	-
JSHIN	11-15	minimum column to be shaded	-
JSHAX	16-20	maximum column to be shaded	-
NSHADE	21-25	shade intensity	-

CARD TEN (6I5)

IRMIN	1- 5	minimum row to be plotted on parametric plot	-
IRMAX	6-10	maximum row to be plotted on parametric plot	-
JRMIN	11-15	minimum column to be plotted on parametric plot	-
JRMAX	16-20	maximum column to be plotted on parametric plot	-
MPODE	21-25	variable plotted (see table C.1)	-

CARD ELEVEN (4F10.4,39X,I1)

TPLTMI	1-10	minimum plot time	S
TPLTMA	11-20	maximum plot time	S
TPLTDL	21-30	Time interval for spatial and time history plots	S
TPLTDE	31-40	time interval for grid plots	S
INUMM	80	(0) last plot set, otherwise (1)	-

Table C.1. Variable Assignments for Cell (I,J) for Subroutines Graph and RDPLT

1	I	radial index	-
2	J	axial index	-
3	R	radial coordinate	C
4	Z	axial coordinate	C
5	DR	cell dimension in radial direction	C
6	DZ	cell dimension in axial direction	C
7	U	axial velocity	C/S
8	V	radial velocity	C/S
9	P	pressure	A
10	E	total energy/unit mass	E/G

11	INT	internal energy/unit mass	E/G
12	C	speed of sound	C/S
13	MACH	Mach number	-
14	RHO	density	G/C ³
15	M	mass	G
16	BO	magnetic field - azimuthal direction	GA
17	TRR	stress - radial direction	D/C ²
18	TZZ	stress - axial direction	D/C ²
19	TOO	stress - azimuthal direction	D/C ²
20	TRZ	shear	D/C ²
21	ER	electric field - radial direction	GA·C/S
22	EZ	electric field - axial direction	GA·C/S
23	VISC	laminar viscosity	P
24	BR	magnetic field - radial direction	GA
25	BZ	magnetic field - axial direction	GA
26	JR	current - radial direction	AC/S·C ²
27	JZ	current - axial direction	AC/S·C ²
28	GAMMA	specific heat ratio	-
29	SIG	electrical conductivity	10 ⁻¹¹ MHO
30	-	-	-
31	TEMP	temperature	K
32	PHI	electrical potential	-
33	PSI	stream current function	-
34	BETA	hall parameter	-
35	COND	thermal conductivity	GC/S ³ ·K
36	VORT	vorticity	1/S

As an example of data input Figure C.2 depicts the input for a simple MHD generator. Output consists of a list of hydrodynamic (Figure C.3), viscous (Figure C.4), or electromagnetic (Figure C.5) variables for cells at intervals KPDEL and JPDEL. If NDIGPL is GT 0, then a digital plot (on-line printer) is produced (Figure C.6).

J	I	POTENTIAL	STREAM FNCT	B	BETA	ELECT COND	JZ	JR	EZ	ER
		VOLTS/E8	AMPC/CH38	GAUSS		MHO/Y E11	AMP/CH2	AMP/CH2	GAUSS/SEC	GAUSS CM/SEC
1	42	-R	-R	.20000E+05	0.	.10000E-09	0.	0.	-R	-R
1	37	-R	-R	.20000E+05	0.	.10000E-09	0.	0.	-R	-R
1	32	-R	-R	.20000E+05	0.	.10000E-09	0.	0.	-R	-R
1	27	-R	-R	.20000E+05	0.	.10000E-09	0.	0.	-R	-R
1	22	-R	-R	.20000E+05	0.	.10000E-09	0.	0.	-R	-R
1	17	-R	-R	.20000E+05	0.	.10000E-09	0.	0.	-R	-R
1	12	-R	-R	.20000E+05	0.	.10000E-09	0.	0.	-R	-R
1	7	-R	-R	.20000E+05	0.	.10000E-09	0.	0.	-R	-R
1	2	-R	-R	.20000E+05	0.	.10000E-09	0.	0.	-R	-R

J	I	POTENTIAL	STREAM FNCT	B	BETA	ELECT COND	JZ	JR	EZ	ER
		VOLTS/E8	AMPC/CH38	GAUSS		MHO/Y E11	AMP/CH2	AMP/CH2	GAUSS/SEC	GAUSS CM/SEC
6	42	0.	-R	.20000E+05	0.	.10000E-09	0.	0.	-R	-R
6	37	.10936E+00	0.	.20000E+05	0.	.10000E-09	.26039E-02	.45753E-02	.26039E+08	.45753E+08
6	32	.62027E+01	.49677E-01	.20000E+05	0.	.10000E-09	.99684E-02	.19027E-01	.11725E+00	.40034E+00
6	27	.62027E+01	.47927E-01	.20000E+05	0.	.10000E-09	.10494E-01	.12550E-01	.11922E+00	.34428E+00
6	22	.56665E+01	.63144E-01	.20000E+05	0.	.10000E-09	.10234E-02	.20246E-01	.47567E+08	.26924E+09
6	17	.62285E+01	.52337E-01	.20000E+05	0.	.10000E-09	.91843E-02	.14995E-01	.68700E+07	.26597E+09
6	12	.15990E+01	.74574E-01	.20000E+05	0.	.10000E-09	.10543E-02	.17826E-02	.92192E+09	.74880E+09
6	7	.78405E+00	-.25314E-02	.20000E+05	0.	.10000E-09	0.	0.	0.	0.
6	2	.78405E+00	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.

J	I	POTENTIAL	STREAM FNCT	B	BETA	ELECT COND	JZ	JR	EZ	ER
		VOLTS/E8	AMPC/CH38	GAUSS		MHO/Y E11	AMP/CH2	AMP/CH2	GAUSS/SEC	GAUSS CM/SEC
11	42	.78405E+00	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.
11	37	.78405E+00	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.
11	32	.34287E+01	0.	.20000E+05	0.	.10000E-09	.10030E+00	.39010E-01	.410030E+10	.39010E+09
11	27	.25930E+01	.47434E+00	.20000E+05	0.	.10000E-09	.30512E-01	.24335E-01	.84512E+08	.16534E+10
11	22	.25930E+01	.27864E+00	.20000E+05	0.	.10000E-09	.95212E-02	.56004E-01	.43607E+08	.71987E+10
11	17	.32842E+01	.13894E+00	.20000E+05	0.	.10000E-09	.30537E-01	.55386E-01	.91082E+08	.16591E+10
11	12	.77125E+00	.10811E+00	.20000E+05	0.	.10000E-09	0.	0.	0.	0.
11	7	0.	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.
11	2	.77125E+00	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.

J	I	POTENTIAL	STREAM FNCT	B	BETA	ELECT COND	JZ	JR	EZ	ER
		VOLTS/E8	AMPC/CH38	GAUSS		MHO/Y E11	AMP/CH2	AMP/CH2	GAUSS/SEC	GAUSS CM/SEC
16	42	.77125E+00	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.
16	37	0.	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.
16	32	.10643E+02	.18944E-01	.20000E+05	0.	.10000E-09	.48001E-01	.46379E-02	.11666E+10	.20805E+10
16	27	.25387E+02	.23914E+00	.20000E+05	0.	.10000E-09	.89366E-02	.17347E-01	.19115E+10	.30055E+10
16	22	.75072E+02	.49700E+00	.20000E+05	0.	.10000E-09	.62769E-02	.87870E-01	.92570E+09	.25777E+10
16	17	.15086E+02	.27826E+00	.20000E+05	0.	.10000E-09	.22565E-01	.15019E-01	.15214E+10	.23650E+10
16	12	.13648E+01	.47194E-01	.20000E+05	0.	.10000E-09	.68272E-01	.46889E-03	.15406E+10	.22505E+10
16	7	.13648E+01	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.
16	2	.13648E+01	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.

J	I	POTENTIAL	STREAM FNCT	B	BETA	ELECT COND	JZ	JR	EZ	ER
		VOLTS/E8	AMPC/CH38	GAUSS		MHO/Y E11	AMP/CH2	AMP/CH2	GAUSS/SEC	GAUSS CM/SEC
21	42	.13648E+01	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.
21	37	.16535E+00	0.	.20000E+05	0.	.10000E-09	.12000E-01	0.	.2000E+09	0.
21	32	.40312E+01	.30366E-01	.20000E+05	0.	.10000E-09	.49152E-01	.22738E-03	.15379E+09	.20932E+10
21	27	.12861E+02	.34200E-01	.20000E+05	0.	.10000E-09	.39779E-01	.34177E-01	.84768E+09	.32137E+10
21	22	.14098E+02	.17475E+00	.20000E+05	0.	.10000E-09	.63769E-02	.64474E-01	.13761E+09	.35967E+10
21	17	.17999E+02	.14229E+00	.20000E+05	0.	.10000E-09	.3196E-01	.45059E-01	.24974E+07	.34455E+10
21	12	.12044E+01	.10104E-01	.20000E+05	0.	.10000E-09	.18074E-01	.15688E-02	.39632E+09	.22193E+10
21	7	.12044E+01	-.11605E-01	.20000E+05	0.	.10000E-09	0.	0.	.68596E-03	.66596E+07
21	2	.12044E+01	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.

J	I	POTENTIAL	STREAM FNCT	B	BETA	ELECT COND	JZ	JR	EZ	ER
		VOLTS/E8	AMPC/CH38	GAUSS		MHO/Y E11	AMP/CH2	AMP/CH2	GAUSS/SEC	GAUSS CM/SEC
26	42	.12044E+01	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.
26	37	.12044E+01	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.
26	32	.22638E+01	.78774E-01	.20000E+05	0.	.10000E-09	.13153E-01	.10122E-01	.13901E+09	.32543E+08
26	27	.19311E+01	.44970E-01	.20000E+05	0.	.10000E-09	.62573E-02	.15176E-01	.19405E+09	.19224E+08
26	22	.53833E+00	.28122E-01	.20000E+05	0.	.10000E-09	.14653E-02	.20545E-01	.24644E+08	.18076E+10
26	17	.23745E+01	.40365E-01	.20000E+05	0.	.10000E-09	.84390E-02	.16834E-01	.21786E+09	.22346E+10
26	12	.17999E+02	.4360E-01	.20000E+05	0.	.10000E-09	.18074E-01	.11196E-01	.15736E+08	.34762E+10
26	7	.16666E+01	0.	.20000E+05	0.	.10000E-09	.22086E-01	0.	.40798E+09	.48942E+10
26	2	.16666E+01	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.

J	I	POTENTIAL	STREAM FNCT	B	BETA	ELECT COND	JZ	JR	EZ	ER
		VOLTS/E8	AMPC/CH38	GAUSS		MHO/Y E11	AMP/CH2	AMP/CH2	GAUSS/SEC	GAUSS CM/SEC
31	42	.13410E+02	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.
31	37	.13410E+02	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.
31	32	.13096E+02	.21554E+00	.20000E+05	0.	.10000E-09	.21650E+00	.92663E-01	.21650E+10	.92663E+09
31	27	.13962E+02	.22742E+00	.20000E+05	0.	.10000E-09	.66596E-02	.78098E-01	.12988E+09	.19988E+09
31	22	.13911E+02	.24067E+00	.20000E+05	0.	.10000E-09	.46135E-02	.70649E-01	.20299E+08	.13643E+10
31	17	.13777E+02	.24237E+00	.20000E+05	0.	.10000E-09	.52969E-03	.48912E-01	.24974E+07	.34455E+10
31	12	.13513E+02	.22294E+00	.20000E+05	0.	.10000E-09	.46675E-02	.70000E-01	.26762E+08	.13887E+10
31	7	.13110E+02	.21105E+00	.20000E+05	0.	.10000E-09	.65909E-02	.74520E-01	.16029E+08	.97730E+09
31	2	.13110E+02	0.	.20000E+05	0.	.10000E-09	.22181E-02	.89882E-01	.31074E+08	.55423E+09

J	I	POTENTIAL	STREAM FNCT	B	BETA	ELECT COND	JZ	JR	EZ	ER
		VOLTS/E8	AMPC/CH38	GAUSS		MHO/Y E11	AMP/CH2	AMP/CH2	GAUSS/SEC	GAUSS CM/SEC
36	42	.13110E+02	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.
36	37	.60381E+02	.60488E+00	.20000E+05	0.	.10000E-09	.60405E+00	.10218E+00	.60405E+10	.10218E+10
36	32	.59409E+02	.59452E+00	.20000E+05	0.	.10000E-09	.10463E+00	.23426E-01	.13747E+09	.54977E+09
36	27	.59008E+02	.57082E+00	.20000E+05	0.	.10000E-09	.47431E-02	.81645E-01	.56464E+08	.11666E+10
36	22	.58909E+02	.56508E+00	.20000E+05	0.	.10000E-09	.65553E-03	.77804E-01	.13122E+08	.89388E+09
36	17	.59181E+02	.55695E+00	.20000E+05	0.	.10000E-09	.28766E-02	.87918E-01	.30652E+08	.11728E+10
36	12	.59663E+02	.68171E+00	.20000E+05	0.	.10000E-09	.89418E-02	.89580E-01	.11279E+09	.72196E+09
36	7	.59931E+02	.59599E+00	.20000E+05	0.	.10000E-09	.10135E-02	.10038E+00	.47920E+06	.29171E+09
36	2	.59931E+02	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.

J	I	POTENTIAL	STREAM FNCT	B	BETA	ELECT COND	JZ	JR	EZ	ER
		VOLTS/E8	AMPC/CH38	GAUSS		MHO/Y E11	AMP/CH2	AMP/CH2	GAUSS/SEC	GAUSS CM/SEC
41	42	.59931E+02	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.
41	37	.15545E+03	.11900E+01	.20000E+05	0.	.10000E-09	.11374E+01	.35816E-01	.11374E+11	.35816E+09
41	32	.15992E+03	.96957E+00	.20000E+05	0.	.10000E-09	.64428E-01	.61376E-01	.62632E+09	.17728E+09
41	27	.15001E+03	.89247E+00	.20000E+05	0.	.10000E-09	.15104E-01	.18498E-01	.10381E+09	.12231E+10
41	22	.14980E+03	.87374E+00	.20000E+05	0.	.10000E-09	.22504E-02	.66296E-01	.25430E+08	.11074E+10
41	17	.15035E+03	.88462E+00	.20000E+05	0.	.10000E-09	.93463E-02	.66407E-01	.59937E+08	.12465E+10
41	12	.15367E+03	.93698E+00	.20000E+05	0.	.10000E-09	.42853E-01	.61726E-01	.30653E+09	.37365E+09
41	7	.16651E+03	.11373E+01	.20000E+05	0.	.10000E-09	.11275E+00	0.	.11089E+10	.12849E+10
41	2	.16651E+03	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.

J	I	POTENTIAL	STREAM FNCT	B	BETA	ELECT COND	JZ	JR	EZ	ER
		VOLTS/E8	AMPC/CH38	GAUSS		MHO/Y E11	AMP/CH2	AMP/CH2	GAUSS/SEC	GAUSS CM/SEC
46	42	.16651E+03	0.	.20000E+05	0.	.10000E-09	0.	0.	0.	0.
46	37	.26300E+03	.11619E+01	.20000E+05	0.	.10000E-09	.11608E+01	.34668E-01	.11608E+11	.34668E+09
46	32	.26319E+03	.11479E+01	.20000E+05	0.	.10000E-09	.70773E-02	.66292E-01	.62468E+08	.10276E+10
46	27	.26330E+03	.11226E+01	.20000E+05	0.	.10000E-09	.75937E-02	.66292E-01	.62468E+08	.10276E+10
46	22	.26330E+03	.11226E+01	.20000E+05	0.	.10000E-09	.29586E-02	.64661E-01	.26629E+08	.12393E+10
46	17	.26279E+03</								

J	I	POTENTIAL	STREAM FNCT	B	BETA	ELECT COND	JZ	JR	EZ	ER
		VOLTS/EB	AMP/CH3B	GAUSS		RHO/M E11	AMP/CH2	AMP/CH2	GAUSS/SEC	GAUSS/SEC
51	42	262143E+03	0	14576E+01	20000E+05	0	10000E-09	0	11261E+10	11261E+10
51	37	262143E+03	0	14576E+01	20000E+05	0	10000E-09	0	11261E+10	11261E+10
51	32	380339E+03	0	14312E+01	20000E+05	0	10000E-09	0	61027E+09	61027E+09
51	27	37999E+03	0	13728E+01	20000E+05	0	10000E-09	0	10959E+08	10959E+08
51	22	37949E+03	0	13407E+01	20000E+05	0	10000E-09	0	38866E+08	38866E+08
51	17	37949E+03	0	13407E+01	20000E+05	0	10000E-09	0	17745E+10	17745E+10
51	12	37922E+03	0	13407E+01	20000E+05	0	10000E-09	0	71323E+09	71323E+09
51	7	37930E+03	0	14027E+01	20000E+05	0	10000E-09	0	45977E+09	45977E+09
51	2	37930E+03	0	14027E+01	20000E+05	0	10000E-09	0	45977E+09	45977E+09
J	I	POTENTIAL	STREAM FNCT	B	BETA	ELECT COND	JZ	JR	EZ	ER
		VOLTS/EB	AMP/CH3B	GAUSS		RHO/M E11	AMP/CH2	AMP/CH2	GAUSS/SEC	GAUSS/SEC
56	42	37930E+03	0	20000E+05	0	10000E-09	0	0	0	0
56	37	59176E+03	0	20000E+05	0	10000E-09	0	0	0	0
56	32	59176E+03	0	19572E+01	20000E+05	0	10000E-09	0	57170E+09	57170E+09
56	27	56284E+03	0	15612E+01	20000E+05	0	10000E-09	0	26553E+09	26553E+09
56	22	56234E+03	0	16709E+01	20000E+05	0	10000E-09	0	72178E+09	72178E+09
56	17	5654E+03	0	15414E+01	20000E+05	0	10000E-09	0	39567E+09	39567E+09
56	12	57472E+03	0	17422E+01	20000E+05	0	10000E-09	0	17739E+09	17739E+09
56	7	51426E+03	0	2408E+01	20000E+05	0	10000E-09	0	33311E+10	33311E+10
56	2	51426E+03	0	2408E+01	20000E+05	0	10000E-09	0	10398E+10	10398E+10
J	I	POTENTIAL	STREAM FNCT	B	BETA	ELECT COND	JZ	JR	EZ	ER
		VOLTS/EB	AMP/CH3B	GAUSS		RHO/M E11	AMP/CH2	AMP/CH2	GAUSS/SEC	GAUSS/SEC
61	42	61426E+03	0	20000E+05	0	10000E-09	0	0	0	0
61	37	79190E+03	0	20886E+01	20000E+05	0	10000E-09	0	56079E+11	56079E+11
61	32	78588E+03	0	20757E+01	20000E+05	0	10000E-09	0	57825E+09	57825E+09
61	27	78588E+03	0	18759E+01	20000E+05	0	10000E-09	0	59049E+09	59049E+09
61	22	78118E+03	0	18146E+01	20000E+05	0	10000E-09	0	74392E+09	74392E+09
61	17	78415E+03	0	18447E+01	20000E+05	0	10000E-09	0	61539E+09	61539E+09
61	12	79138E+03	0	18142E+01	20000E+05	0	10000E-09	0	20326E+09	20326E+09
61	7	79153E+03	0	20613E+01	20000E+05	0	10000E-09	0	56928E+09	56928E+09
61	2	79153E+03	0	20613E+01	20000E+05	0	10000E-09	0	56928E+09	56928E+09
J	I	POTENTIAL	STREAM FNCT	B	BETA	ELECT COND	JZ	JR	EZ	ER
		VOLTS/EB	AMP/CH3B	GAUSS		RHO/M E11	AMP/CH2	AMP/CH2	GAUSS/SEC	GAUSS/SEC
66	42	79153E+03	0	20000E+05	0	10000E-09	0	0	0	0
66	37	96877E+03	0	21266E+01	20000E+05	0	10000E-09	0	41890E+09	41890E+09
66	32	96764E+03	0	21174E+01	20000E+05	0	10000E-09	0	43004E+09	43004E+09
66	27	96599E+03	0	20451E+01	20000E+05	0	10000E-09	0	45186E+09	45186E+09
66	22	96599E+03	0	20451E+01	20000E+05	0	10000E-09	0	45186E+09	45186E+09
66	17	96679E+03	0	20561E+01	20000E+05	0	10000E-09	0	43664E+09	43664E+09
66	12	96775E+03	0	20939E+01	20000E+05	0	10000E-09	0	43767E+09	43767E+09
66	7	96775E+03	0	20939E+01	20000E+05	0	10000E-09	0	43767E+09	43767E+09
66	2	96775E+03	0	20939E+01	20000E+05	0	10000E-09	0	43767E+09	43767E+09
J	I	POTENTIAL	STREAM FNCT	B	BETA	ELECT COND	JZ	JR	EZ	ER
		VOLTS/EB	AMP/CH3B	GAUSS		RHO/M E11	AMP/CH2	AMP/CH2	GAUSS/SEC	GAUSS/SEC
71	42	96775E+03	0	20000E+05	0	10000E-09	0	0	0	0
71	37	11668E+04	0	26397E+01	20000E+05	0	10000E-09	0	19177E+09	19177E+09
71	32	11668E+04	0	23023E+01	20000E+05	0	10000E-09	0	33721E+09	33721E+09
71	27	11694E+04	0	22372E+01	20000E+05	0	10000E-09	0	31490E+09	31490E+09
71	22	11620E+04	0	21077E+01	20000E+05	0	10000E-09	0	31490E+09	31490E+09
71	17	11659E+04	0	22194E+01	20000E+05	0	10000E-09	0	31836E+09	31836E+09
71	12	11686E+04	0	2279E+01	20000E+05	0	10000E-09	0	33391E+09	33391E+09
71	7	11771E+04	0	24072E+01	20000E+05	0	10000E-09	0	14323E+07	14323E+07
71	2	11771E+04	0	24072E+01	20000E+05	0	10000E-09	0	14323E+07	14323E+07
J	I	POTENTIAL	STREAM FNCT	B	BETA	ELECT COND	JZ	JR	EZ	ER
		VOLTS/EB	AMP/CH3B	GAUSS		RHO/M E11	AMP/CH2	AMP/CH2	GAUSS/SEC	GAUSS/SEC
76	42	11771E+04	0	20000E+05	0	10000E-09	0	0	0	0
76	37	13776E+04	0	24168E+01	20000E+05	0	10000E-09	0	21297E+11	21297E+11
76	32	13776E+04	0	23647E+01	20000E+05	0	10000E-09	0	81006E+08	81006E+08
76	27	13765E+04	0	23296E+01	20000E+05	0	10000E-09	0	14498E+09	14498E+09
76	22	13763E+04	0	23172E+01	20000E+05	0	10000E-09	0	15636E+09	15636E+09
76	17	13787E+04	0	23455E+01	20000E+05	0	10000E-09	0	10373E+09	10373E+09
76	12	13787E+04	0	23455E+01	20000E+05	0	10000E-09	0	10668E+07	10668E+07
76	7	13810E+04	0	24072E+01	20000E+05	0	10000E-09	0	10668E+07	10668E+07
76	2	13810E+04	0	24072E+01	20000E+05	0	10000E-09	0	10668E+07	10668E+07
J	I	POTENTIAL	STREAM FNCT	B	BETA	ELECT COND	JZ	JR	EZ	ER
		VOLTS/EB	AMP/CH3B	GAUSS		RHO/M E11	AMP/CH2	AMP/CH2	GAUSS/SEC	GAUSS/SEC
81	42	13810E+04	0	20000E+05	0	10000E-09	0	0	0	0
81	37	15832E+04	0	24111E+01	20000E+05	0	10000E-09	0	24070E+11	24070E+11
81	32	15819E+04	0	23777E+01	20000E+05	0	10000E-09	0	36046E+08	36046E+08
81	27	15819E+04	0	23777E+01	20000E+05	0	10000E-09	0	82207E+08	82207E+08
81	22	15817E+04	0	23603E+01	20000E+05	0	10000E-09	0	70451E+08	70451E+08
81	17	15820E+04	0	23622E+01	20000E+05	0	10000E-09	0	86390E+08	86390E+08
81	12	15829E+04	0	2376E+01	20000E+05	0	10000E-09	0	80199E+08	80199E+08
81	7	15840E+04	0	24072E+01	20000E+05	0	10000E-09	0	51336E+08	51336E+08
81	2	15840E+04	0	24072E+01	20000E+05	0	10000E-09	0	37967E+06	37967E+06
J	I	POTENTIAL	STREAM FNCT	B	BETA	ELECT COND	JZ	JR	EZ	ER
		VOLTS/EB	AMP/CH3B	GAUSS		RHO/M E11	AMP/CH2	AMP/CH2	GAUSS/SEC	GAUSS/SEC
86	42	15840E+04	0	20000E+05	0	10000E-09	0	0	0	0
86	37	16852E+04	0	20000E+05	0	10000E-09	0	0	0	0
86	32	16849E+04	0	24031E+01	20000E+05	0	10000E-09	0	7159E+08	7159E+08
86	27	16846E+04	0	23938E+01	20000E+05	0	10000E-09	0	38035E+08	38035E+08
86	22	16845E+04	0	23872E+01	20000E+05	0	10000E-09	0	46367E+08	46367E+08
86	17	16846E+04	0	23879E+01	20000E+05	0	10000E-09	0	46028E+08	46028E+08
86	12	16851E+04	0	23978E+01	20000E+05	0	10000E-09	0	41460E+08	41460E+08
86	7	14828E+04	0	20000E+05	0	10000E-09	0	0	0	0
86	2	14828E+04	0	20000E+05	0	10000E-09	0	0	0	0
J	I	POTENTIAL	STREAM FNCT	B	BETA	ELECT COND	JZ	JR	EZ	ER
		VOLTS/EB	AMP/CH3B	GAUSS		RHO/M E11	AMP/CH2	AMP/CH2	GAUSS/SEC	GAUSS/SEC
91	42	14828E+04	0	20000E+05	0	10000E-09	0	0	0	0
91	37	14828E+04	0	20000E+05	0	10000E-09	0	0	0	0
91	32	16850E+04	0	24079E+01	20000E+05	0	10000E-09	0	74347E+07	74347E+07
91	27	16848E+04	0	2399E+01	20000E+05	0	10000E-09	0	12031E+08	12031E+08
91	22	16847E+04	0	24005E+01	20000E+05	0	10000E-09	0	20131E+08	20131E+08
91	17	16849E+04	0	24007E+01	20000E+05	0	10000E-09	0	17528E+08	17528E+08
91	12	16852E+04	0	24072E+01	20000E+05	0	10000E-09	0	44118E+08	44118E+08
91	7	16852E+04	0	24072E+01	20000E+05	0	10000E-09	0	44118E+08	44118E+08
91	2	16852E+04	0	24072E+01	20000E+05	0	10000E-09	0	44118E+08	44118E+08
J	I	POTENTIAL	STREAM FNCT	B	BETA	ELECT COND	JZ	JR	EZ	ER
		VOLTS/EB	AMP/CH3B	GAUSS		RHO/M E11	AMP/CH2	AMP/CH2	GAUSS/SEC	GAUSS/SEC
96	42	16852E+04	0	20000E+05	0	10000E-09	0	0	0	0
96	37	16852E+04	0	20000E+05	0	10000E-09	0	0	0	0
96	32	16852E+04	0	24070E+01	20000E+05	0	10000E-09	0	51670E+06	51670E+06
96	27	16851E+04	0	24066E+01	20000E+05	0	10000E-09	0	42377E+07	42377E+07
96	22	16851E+04	0	24066E+01	20000E+05	0	10000E-09	0	78135E+07	78135E+07
96	17	16851E+04	0	24075E+01	20000E+05	0	10000E-09	0	81377E+07	81377E+07
96	12	16852E+04	0	24066E+01	20000E+05	0	10000E-09	0	23247E+07	23247E+07
96	7	16852E+04	0	20000E+05	0	10000E-09	0	0	0	0
96	2	16852E+04	0	20000E+05	0	10000E-09	0	0	0	0

Figure C.5 Continued

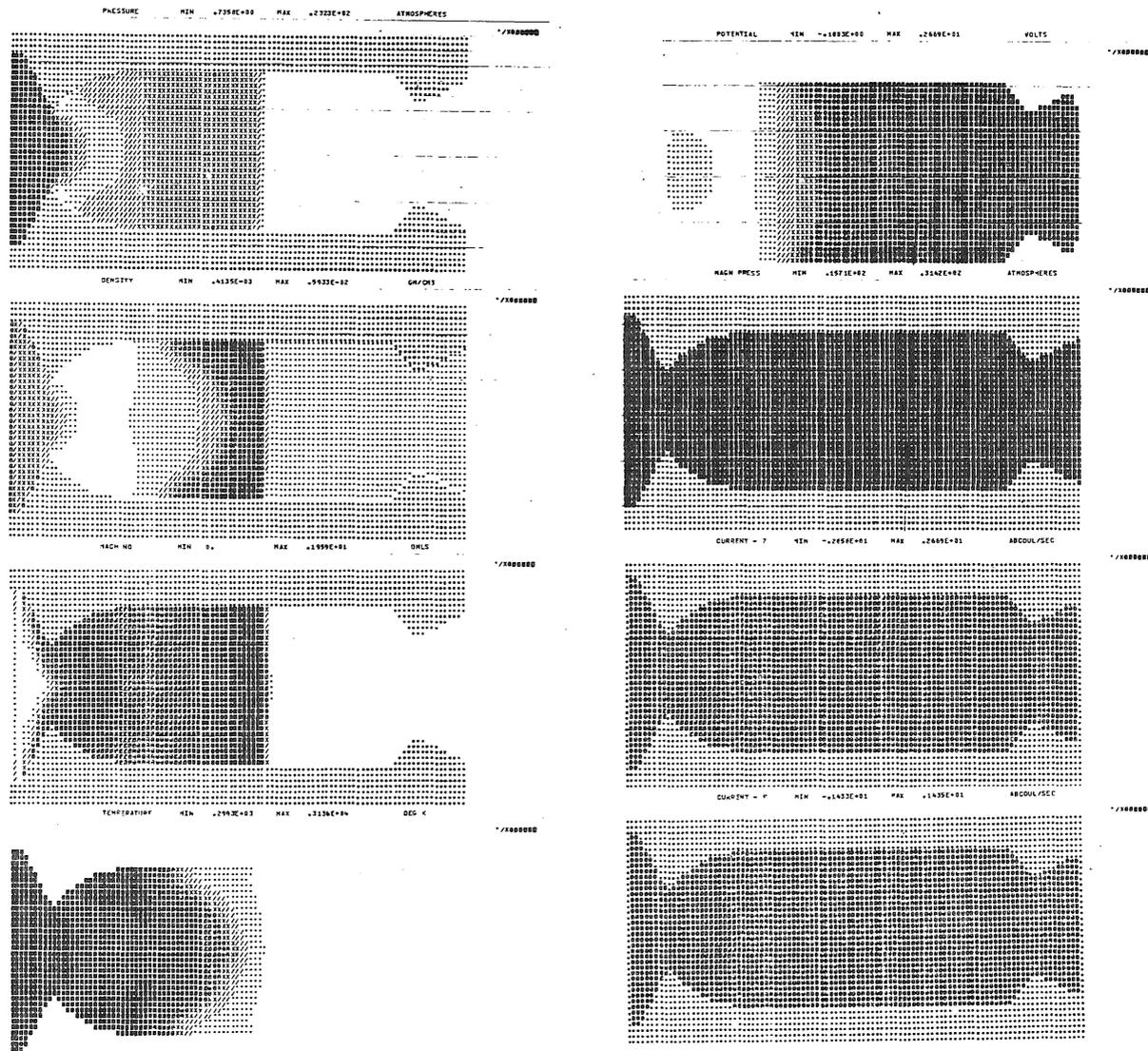


Figure C.6 Digital Plots

Computer graphics for this program consist of the following:

- (1) Time Histories
- (2) Spatial Distributions
- (3) Vectors
- (4) Contour Mapping
- (5) Grey-Level Scaling
- (6) Trace Particles
- (7) Three-Dimensional Perspectives

Animation is easily achieved by generating sixteen or thirty-five mm motion pictures from a sequence of individual frames of the above plots. Sections 3, 4 and 5 of this report contain numerous examples of the graphics which facilitates the analysis of problems under investigation. A brief discussion of each plot follows:

(1) TIME HISTORIES

At a given cell or group of cells, it may be desirable to trace the time history of certain variables such as pressure (Table C.1, Variable (9)). As an example, consider the following input (Fig. C.7), at cell $I = 11$, $J = 3$, pressure is plotted as a function of time.

TPLTDL is normally input as zero, but may be assigned a specified time interval at which time histories are plotted. In the event TPLTDL is zero, NPLOT (hydro input), which specifies the cycle interval at which data is stored to be plotted later, controls the number of time data points. If TPLTMA, TPLTDE or TPLTDL are greater than T (e.g. 1.0), the last hydro cycle time, then TPLTMA, TPLTDE and TPLTDL are set equal to T.

(2) SPATIAL DISTRIBUTIONS

The question often arises as to how certain variables vary in either the axial or radial direction. Consider the MHD generator problem where it is desirable to find the location of a discontinuity along the center-line (Fig. C.8)

ISMIN	ISMAX	JSMIN	JSMAX	MCODE
11	11	1	69	9
11	11	1	69	13
11	11	1	69	14

at cells $I = 11$, $J = 1$, 69, pressure (9), Mach number (13) and temperature (31) are plotted. The axial distribution of pressure, Mach number and temperature reveal the location of this discontinuity at a specific time.

```

MOVIE      IHIST      ISPAT      IPARAM      ILINE      ISC      IDET      ISYM      IVEL      RPV      IPART
0          1          0          0          2          0          0          0          0.0      0          0
ILOW      IHIGH      JLOW      JHIGH      JPDEL      KPDEL
1          22         1          69         1          1
ZLOW      ZHIGH      XLOW      XHIGH
1.000E+01 .8100E+02 -.5200E+02 .2800E+02
IMIN      IMAX      JHMIN      JHMAX      PCODE      MFRAME
1          1          3          3          9          0
ISMIN      ISMAX      JSMIN      JSMAX      NCODE
1          1          1          1          1          2
1          22         22         69         69
TPLTMI    TPLTMA    TPLTDE
0.         .3882E-03  0.
    
```

Input on Card as 1.0 (>.3882E-03) and Program Redefines to this Value

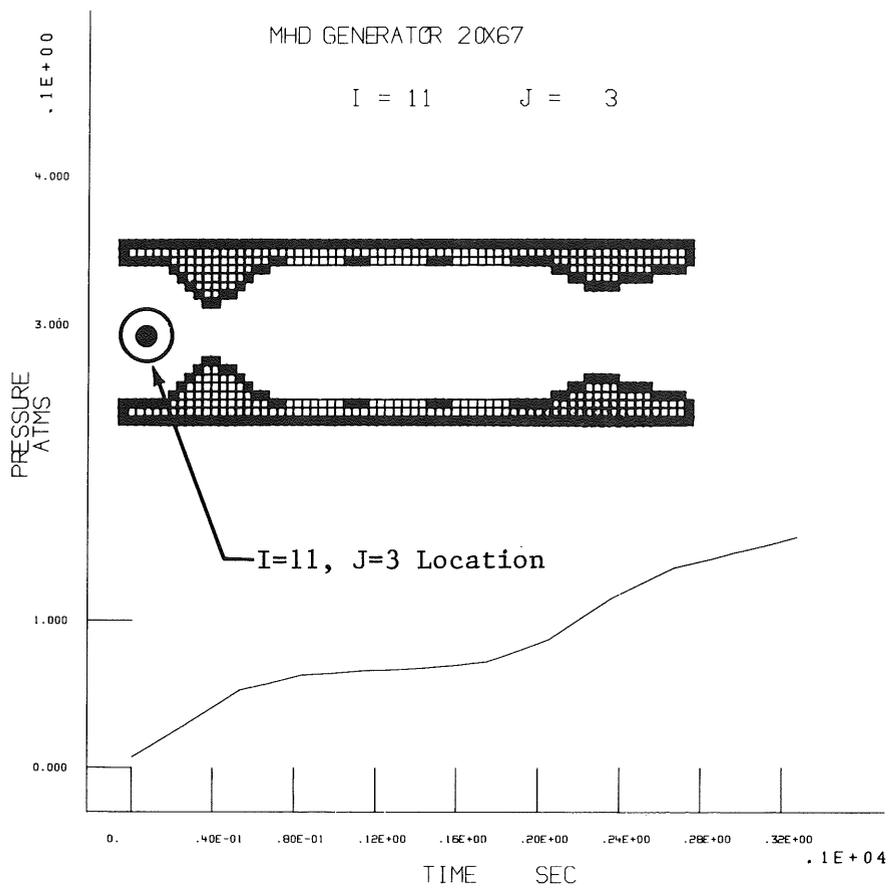


Figure C.7 Time History

```

MOVIE IHIST ISPAT IPARAM ILINE ISC IOEI ISYM IVEL .8V IPART
0 0 3 0 0 0 0 1 .2500E-03 0
ILOW IHIGH JLOW JHIGH JPDEL KPDEL
1 22 1 1 1 1
ZLOW ZHIGH XLOW XHIGH
1.000E+01 1.000E+01 1.000E+02 1.000E+02
IWX 1 2 3 4 5 6 7 8 9 10 11 12
1 1 1 1 1 1 1 1 1 1 1 1
ISMIN ISMAX JSMIN JSMAX NCODE
1 1 1 1 1 1 1 1 1 1 1 1
ILINE IZMIN IZMAX JZMIN JZMAX HZDF MFRAME
1 1 1 1 1 1 1 1 1 1 1 1
IPLTHI 11 11 11 11 11 11 11 11 11 11 11 11
IPLTHA .3099E-03 .3099E-03 .3099E-03 .3099E-03
    
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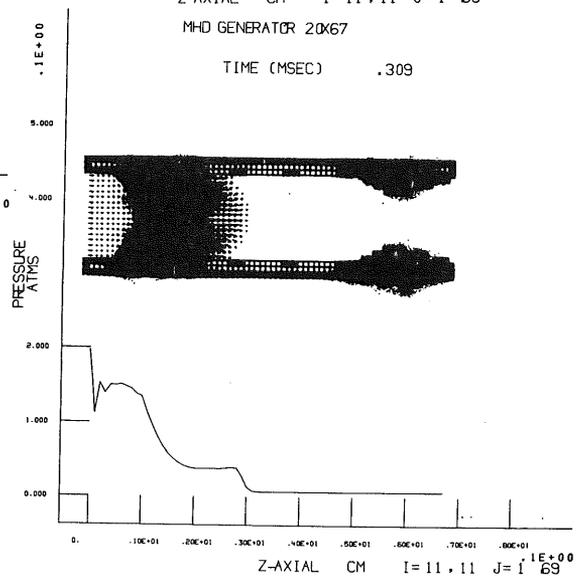
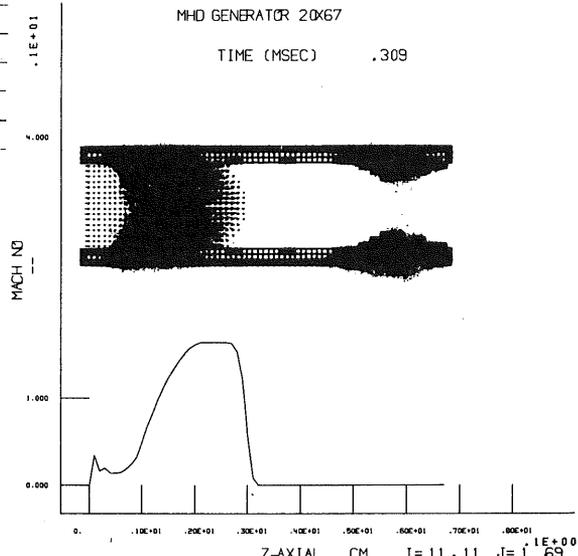
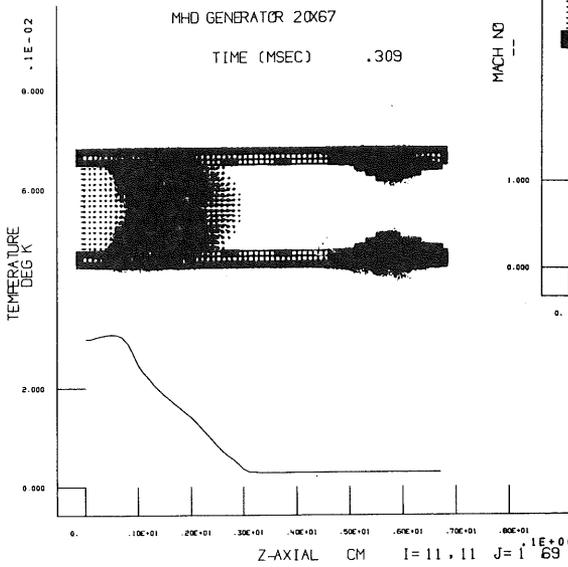


Figure C.8 Spatial Distributions

(3) VECTORS

Vector plots provide a useful tool in examining the magnitude and direction of such variables as the velocity and electric currents or fields.

Given radial and axial vector components at each cell, arrows are drawn with a direction = \tan^{-1} (radial component/axial component) and a magnitude proportional to the square root of the sum of squares of both components. Thus, velocity vectors have a direction = \tan^{-1} (V/U) and magnitude proportional to $\sqrt{v^2}$. The proportional constant RPV was originally meant to represent "rasters per velocity" (cm/sec), where there are 1023 rasters along each axis. If the average velocity is 20000 cm/sec, in order to space vectors without overlapping, RPV is set at approximately 0.001 so that the length of each arrow is approximately 20000 x 0.001 or 20 rasters. Forty or fifty arrows would then comfortably fit in each direction.

As an example of a vector plot, Figure C.9 depicts velocity and current density vectors.

IVEL = 1

RPV = 0.001
(velocity)

RPV = 100.0
(current)

IVX = 8 radial velocity
IVZ = 7 axial velocity

IVX = 26 radial current
IVZ = 27 axial current

JPDEL = 1
KPDEL = 1

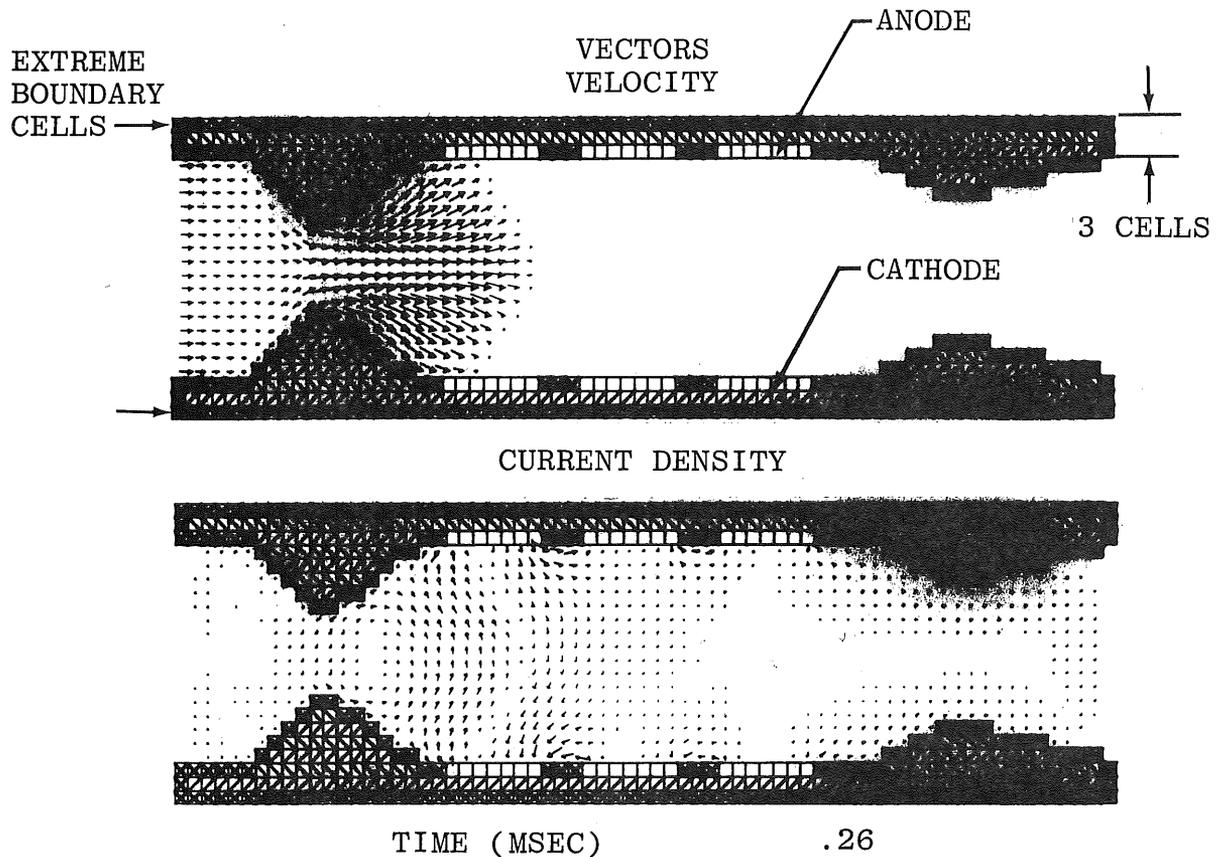
arrows will be drawn at every cell in the axial and radial directions.

(4) CONTOUR MAPPING

Contours are lines of a constant property value. Contour maps illustrate regions of weak or strong gradients and coupled with shade intensity plots or 3-D plots, depict the direction of gradients. Sections (3), (4), and (5) of this report contain numerous examples of contour maps. As a simple example, consider the following input:

MOVIE = 3
ISC = -1
E1 = Minimum Contour Value
E2 = Maximum Contour Value
L11 = Contour Variable (Table C.1)

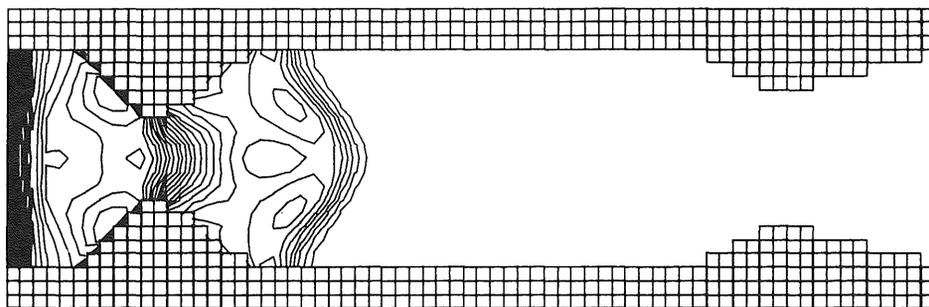
Forty contours (fixed in program) will be drawn whose equidistant values lie between E1 and E2. The contour map for this problem is shown in Fig. C.10. (Input data will be shown later in Fig. C.18).



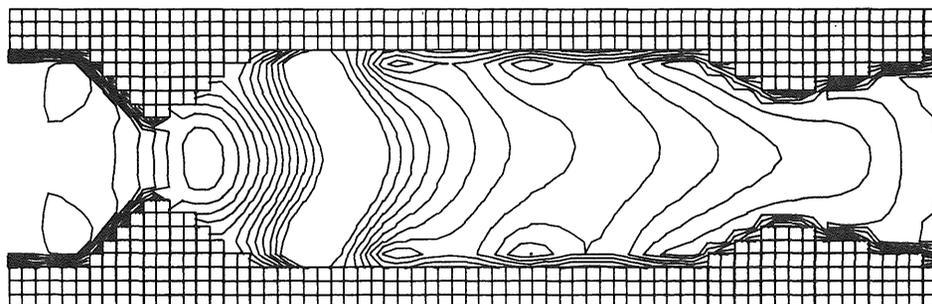
Note: Cells defining the electrode-pairs (anode/cathode) must not lie on the extreme boundary. In the example above, they lie 2 cells below this boundary. Simply make RD values at least $1\frac{1}{2}$ "DR0's" less than R_{max} [= $R(1) + (KP2 - 1) * DR0$] (See Fig. C.2, page 215).

Figure C.9 Vectors

CONTOUR MAP
PRESSURE



CURRENT STREAM FUNCTION



TIME (MSEC) .26

Figure C.10 Contours

(5) GREY-LEVEL SCALING

Grey-level scaling plots are generated by representing each contour region of a contour map by a shade intensity or grey level. The higher the value of the contour parameter in the contour region, the darker or more intense the shading. The advantage to this type of scaling is that it provides a rapid means for analyzing large amounts of data in one concise plot. Contour plots suffer from the difficulty in labelling different contours especially in rapidly changing regions, whereas the combination of shade and contour mapping does so routinely.

The same data for contour mapping is used for shading with the exception that

MOVIE = 0

Figure C.11 reveals a shade/contour map.

(6) TRACE PARTICLES

Trace particles as the name implies, traces or labels the trajectory of a prescribed number of particles in a dynamic media. Initially, particles are defined at specified locations (cells) and assume the velocity and coordinates of that cell. After a series of time increments, the particles move from cell to cell always assuming the velocity and coordinate values of the cell that it lies in. Observing the motion of these particles in time, the motion of the fluid may be more clearly understood.

Figure C.12 illustrates tracer particles and Mach contours.

(7) THREE-DIMENSIONAL PLOTS

The data for creating contours:

Grid Coordinates (X,Y)
Variable Z (e.g., P, M, T, etc.)

can be used just as easily to create a three-dimensional plot. The advantage of the 3-D graph is that gradient directions become apparent (peaks, valleys) whereas they are not so with contours. Numerous 3-D plots are shown in Figures C.13 through C.17. The only difference between contour data input and 3-D data input is that IDET = 5 in the latter case.

In summary, a number of plots have been described which aid in the analysis of computer results. The following graphs further illustrate their contributions.

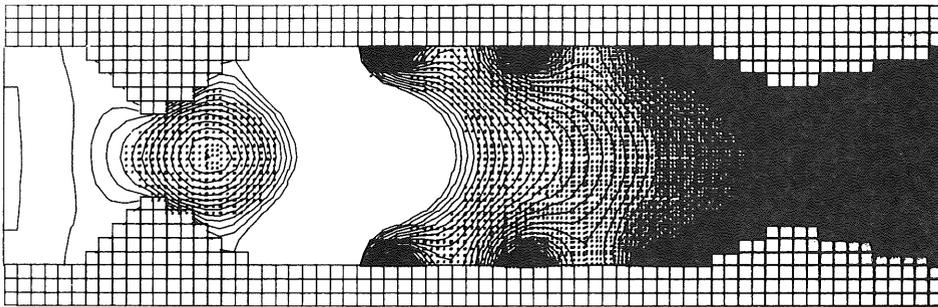


Figure C.11 Grey-Level Scaling

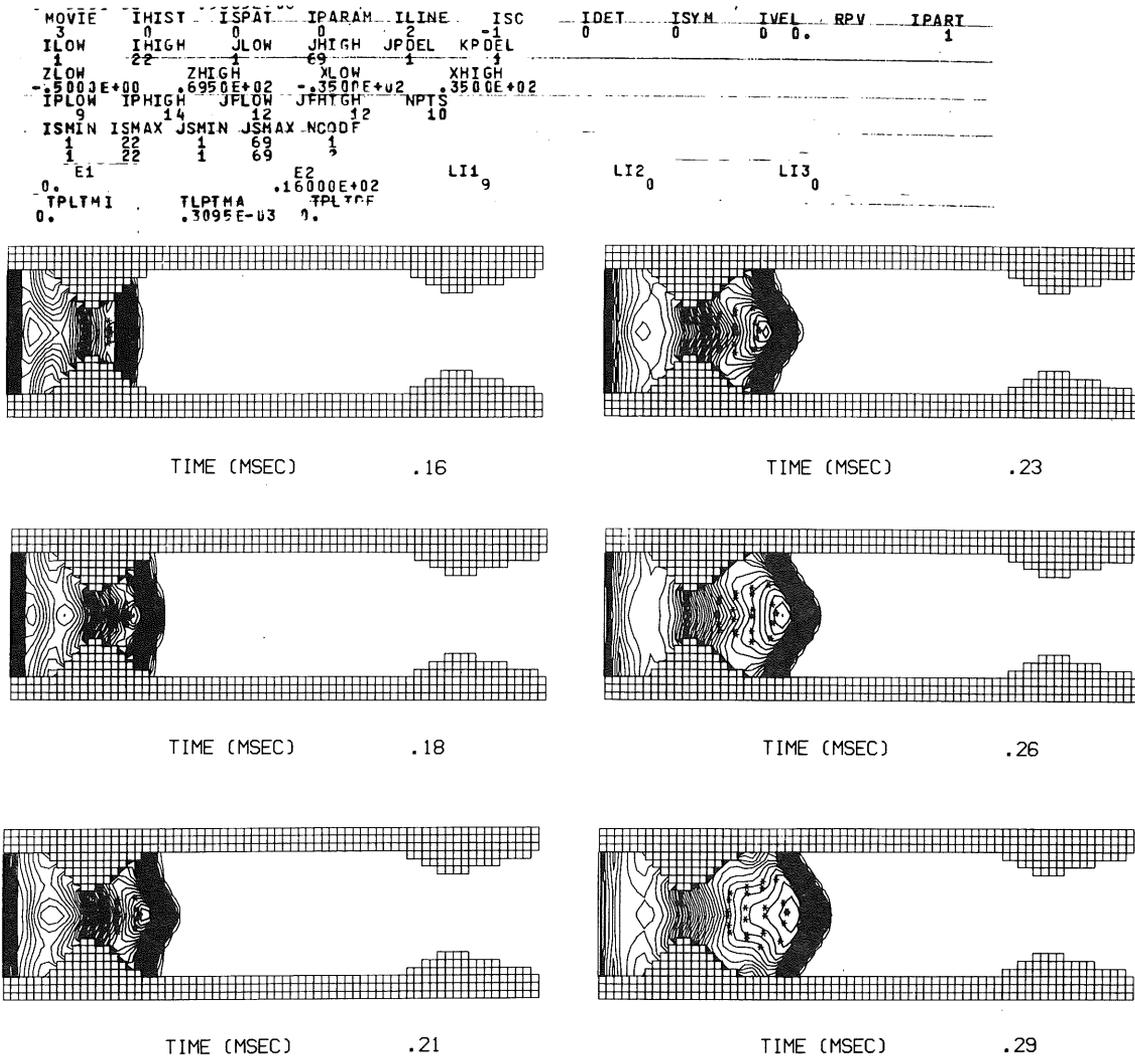


Figure C.12 Trace Particles

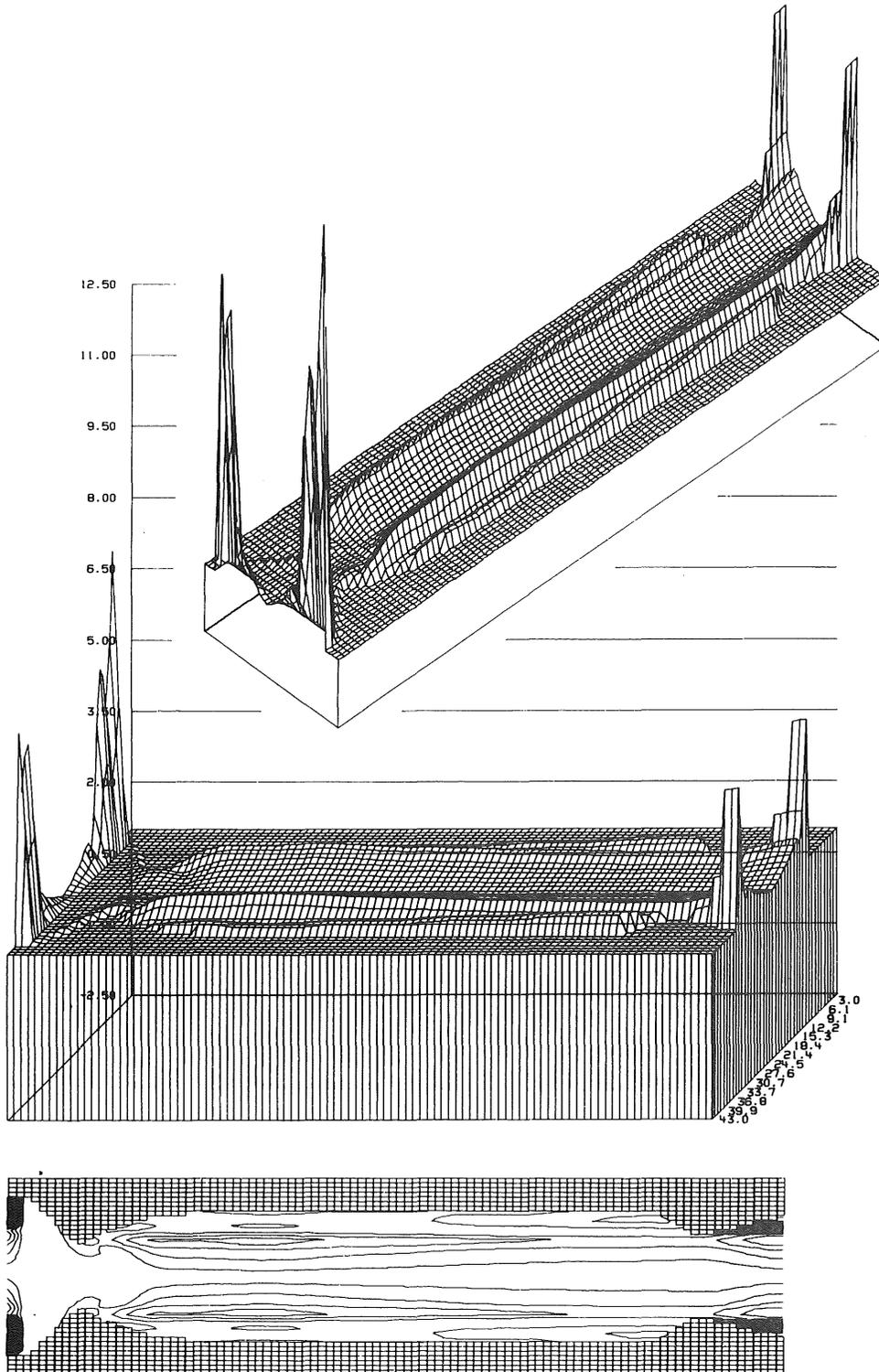


Figure C.13 Three-Dimensional Electric Potential

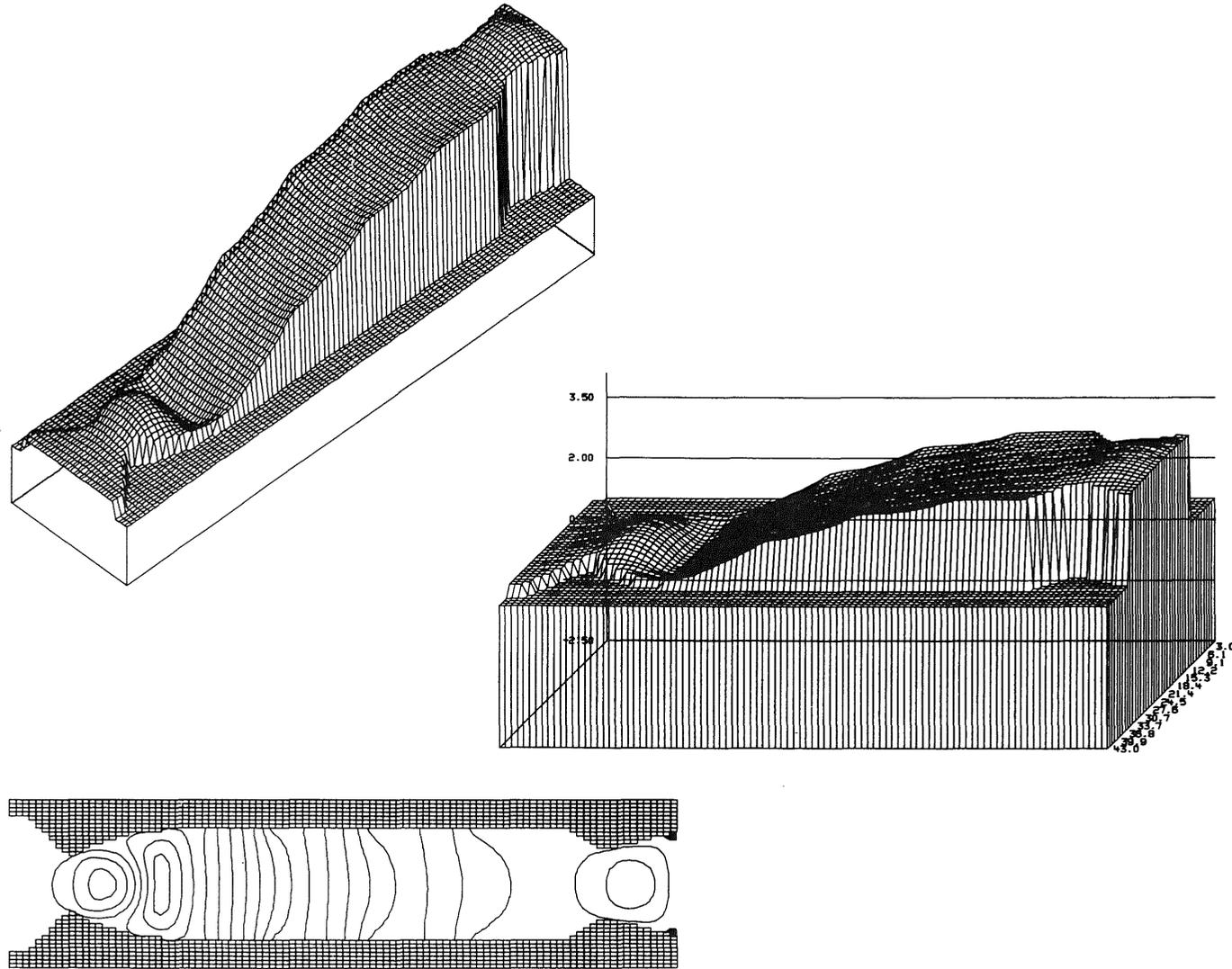


Figure C.14 Three-Dimensional Current Stream Function

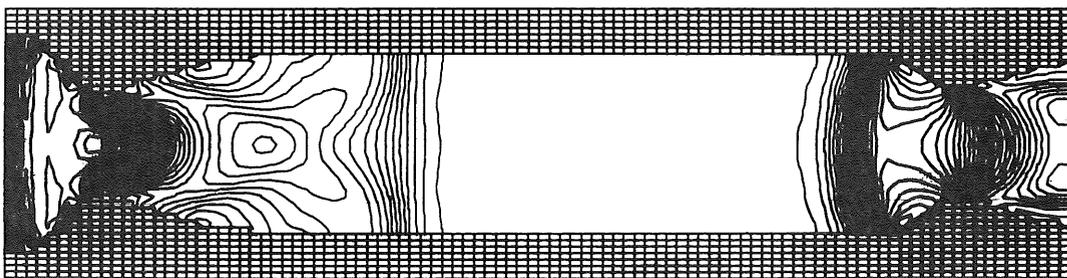
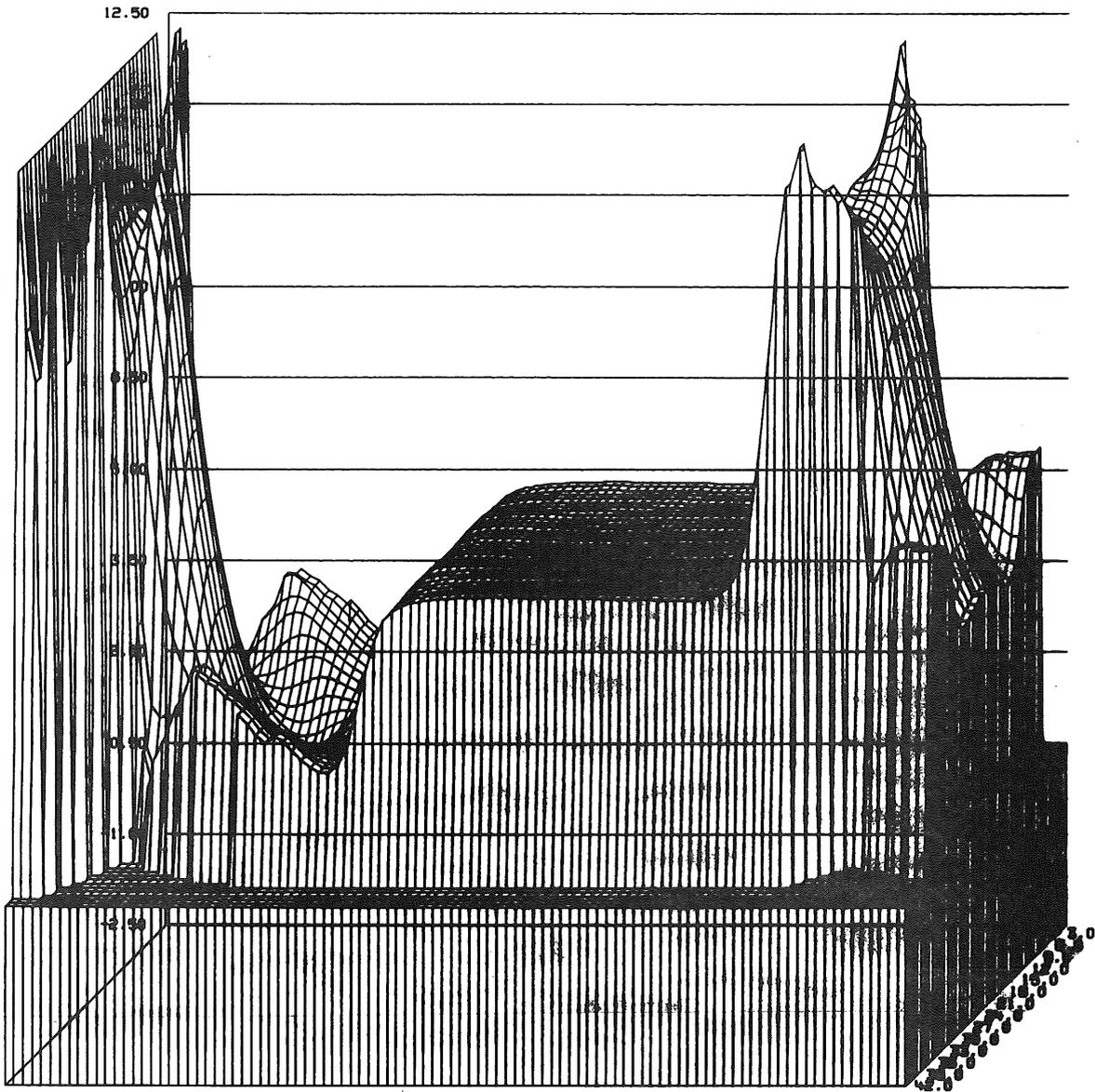


Figure C.15 Three-Dimensional Pressure

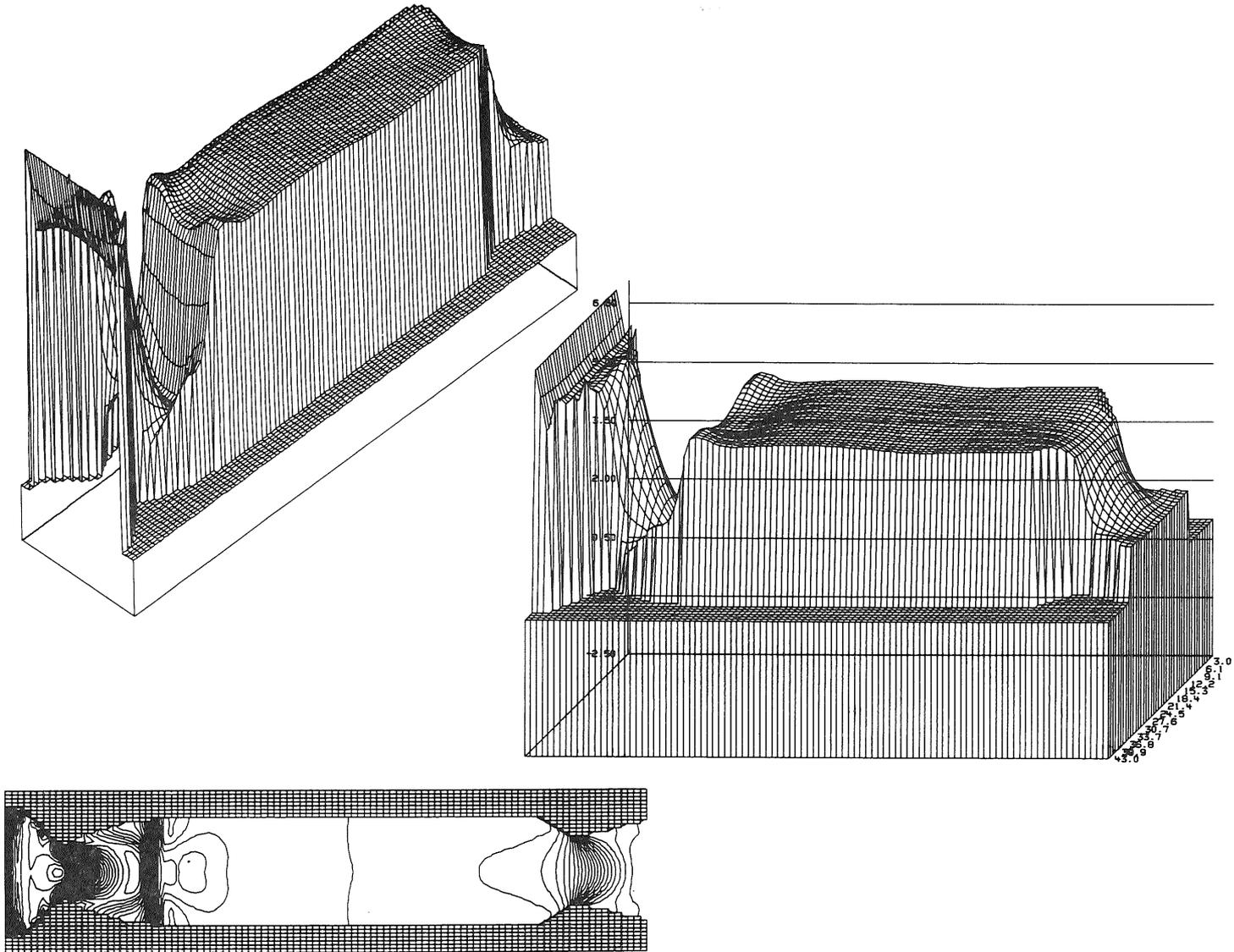


Figure C.16 Three-Dimensional Mach Number

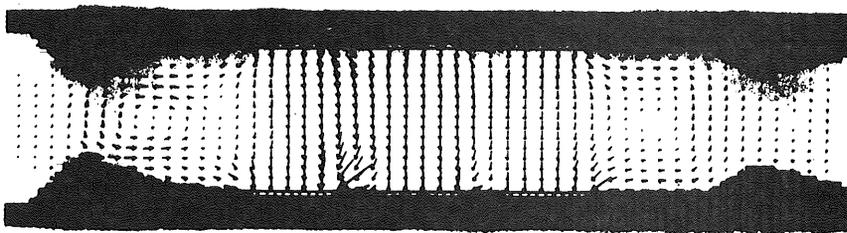
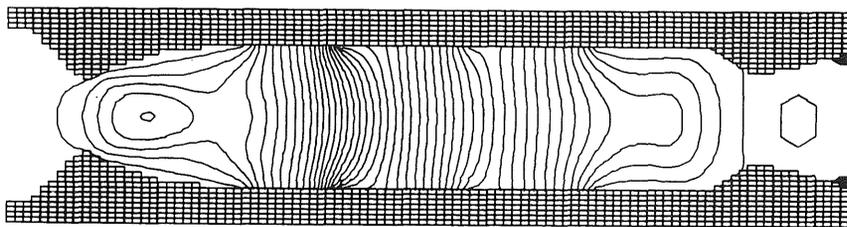
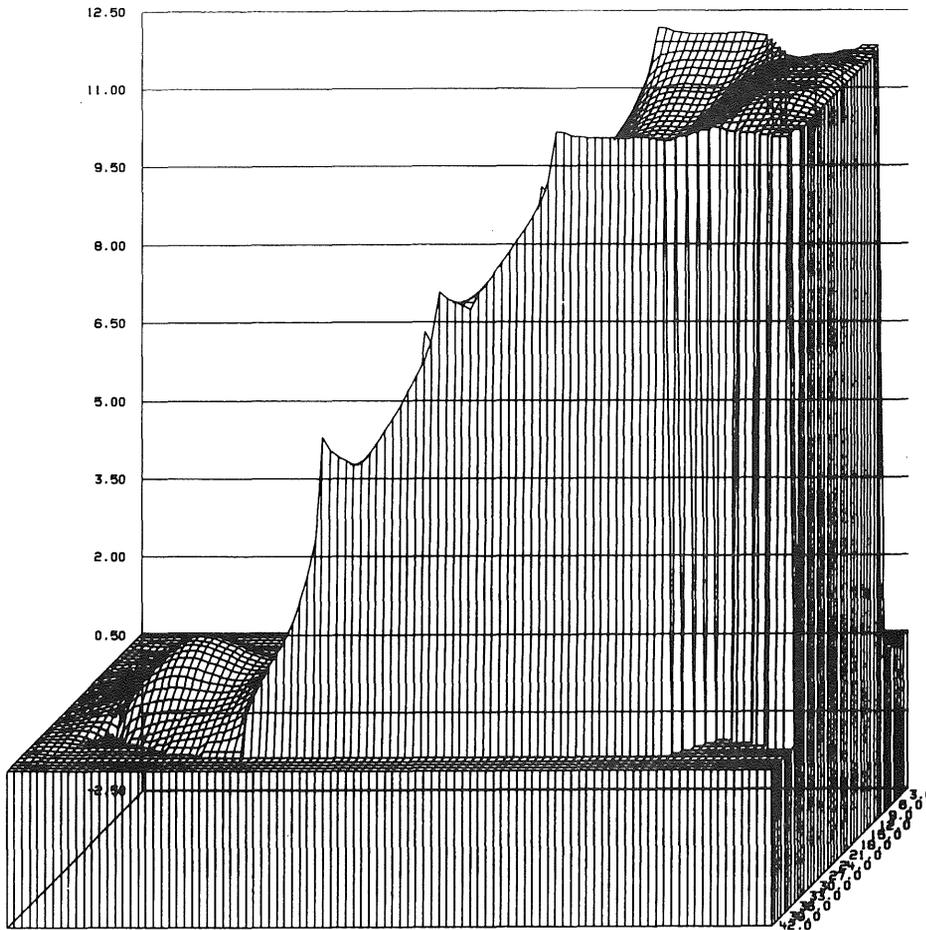
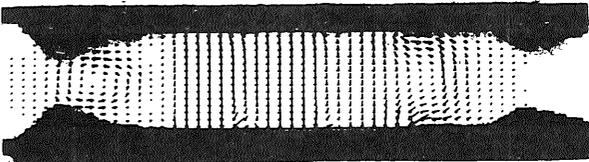
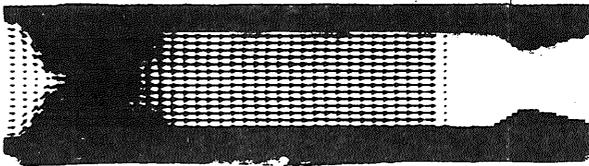
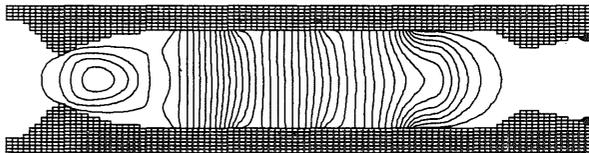
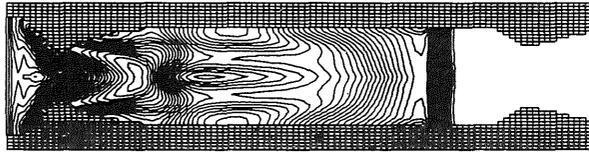


Figure C.17 3-D and Contour Plots of ψ



```

MOVIE  IHIST  ISPAT  IPARAM  ILINE  ISC  IDET  ISYM  IVEL  RPV  IPART
  3      0      0      1      2      -1   5      0      0.0  0.0  0
ILOW  IHIGH  JLOW  JHTGH  JPDEL  KPDEL
  1      42      1      100      1      1
ZLOW  ZHIGH  XLOW  XHIGH
-5.000E+00 .8250E+02 -.4150E+02 .4150E+02
ISMIN ISMAX JSMIN JSMAX NCOEF
  1      42      1      100      1
  1      42      1      100      2
E1
TPLTMI  TPLTMA  TPLTFC  TPLTDL
0.      .2504E-02 .2504E-02 .2504E-02
E2
LI1 13
LI2 0
LI3 0

```

```

MOVIE  IHIST  ISPAT  IPARAM  ILINE  ISC  IDET  ISYM  IVEL  RPV  IPART
  3      0      0      1      2      -1   5      0      0.0  0.0  0
ILOW  IHIGH  JLOW  JHTGH  JPDEL  KPDEL
  1      42      1      100      1      1
ZLOW  ZHIGH  XLOW  XHIGH
-5.000E+00 .8250E+02 -.4150E+02 .4150E+02
ISMIN ISMAX JSMIN JSMAX NCOEF
  1      42      1      100      1
  1      42      1      100      2
E1
TPLTMI  TPLTMA  TPLTFC  TPLTDL
0.      .2504E-02 .2504E-02 .2504E-02
E2
LI1 33
LI2 0
LI3 0

```

```

MOVIE  IHIST  ISPAT  IPARAM  ILINE  ISC  IDET  ISYM  IVEL  RPV  IPART
  0      0      0      0      2      0   1      0      1.2500E-03 0.0  0
ILOW  IHIGH  JLOW  JHTGH  JPDEL  KPDEL
  1      42      1      100      2      2
ZLOW  ZHIGH  XLOW  XHIGH
-5.000E+00 .8250E+02 -.4150E+02 .4150E+02
IVX  IVZ  KLOG
  8      7      0
ISMIN ISMAX JSMIN JSMAX NCOEF
  1      42      1      100      1
  1      42      1      100      2
TPLTMI  TPLTMA  TPLTFC  TPLTDL
0.      .2504E-02 .2504E-02 .2504E-02

```

```

MOVIE  IHIST  ISPAT  IPARAM  ILINE  ISC  IDET  ISYM  IVEL  RPV  IPART
  0      0      0      0      2      0   1      0      1.1000E+03 0.0  0
ILOW  IHIGH  JLOW  JHTGH  JPDEL  KPDEL
  1      42      1      100      2      2
ZLOW  ZHIGH  XLOW  XHIGH
-5.000E+00 .8250E+02 -.4150E+02 .4150E+02
IVX  IVZ  KLOG
  26      27      0
ISMIN ISMAX JSMIN JSMAX NCOEF
  1      42      1      100      1
  1      42      1      100      2
TPLTMI  TPLTMA  TPLTFC  TPLTDL
0.      .2504E-02 .2504E-02 .2504E-02

```

237

Figure C.18 Three Electrode-Pair MHD Generator

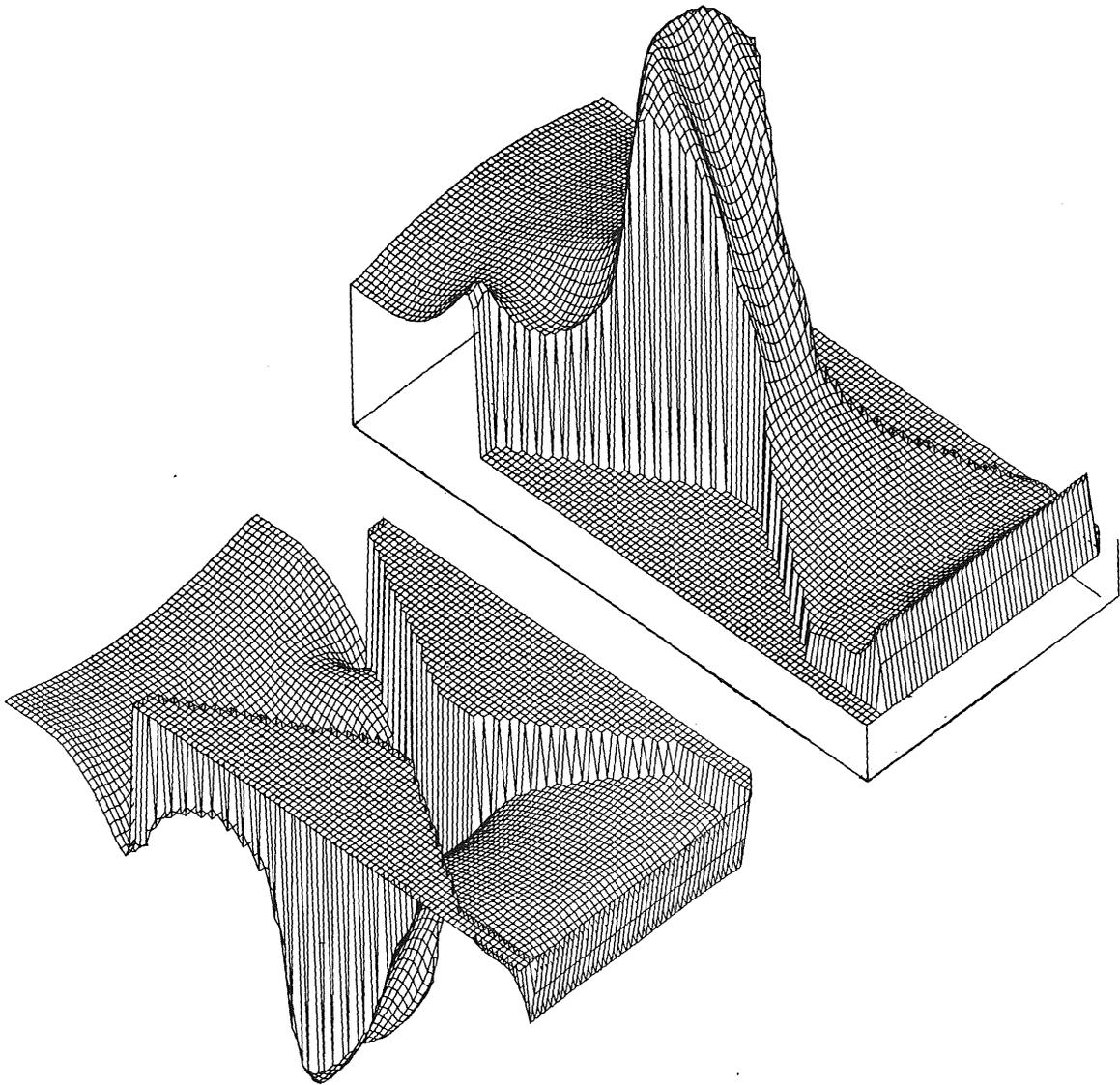


Figure C.19a Shock in a Nozzle, Two 3-D Perspectives

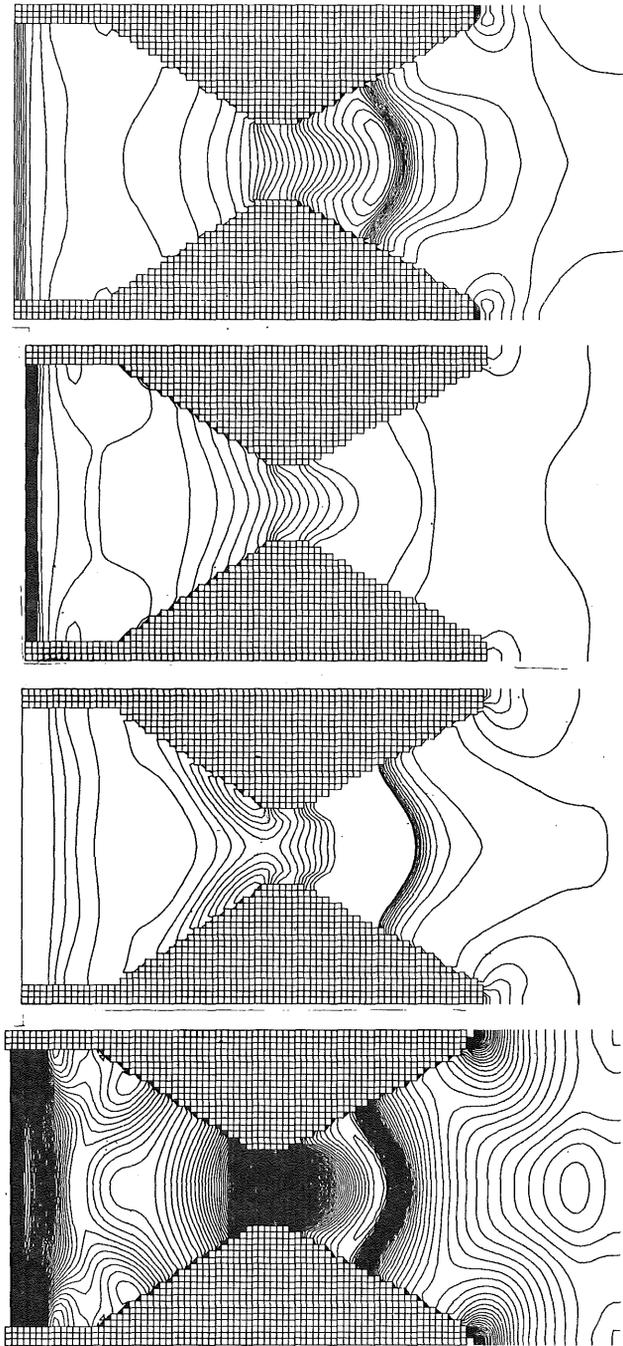


Figure C.19b Nozzle Contours. Pressure, Temperature, Density, Mach Number

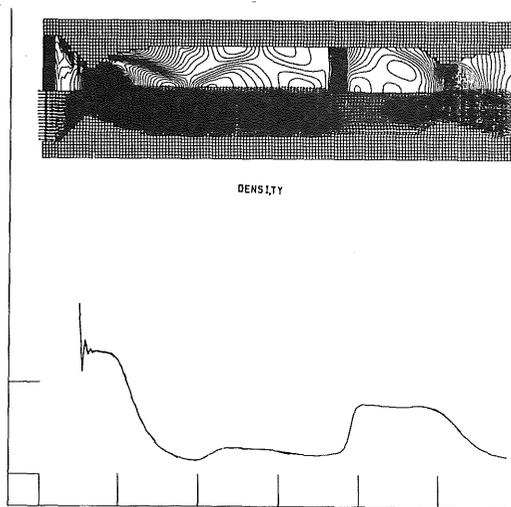
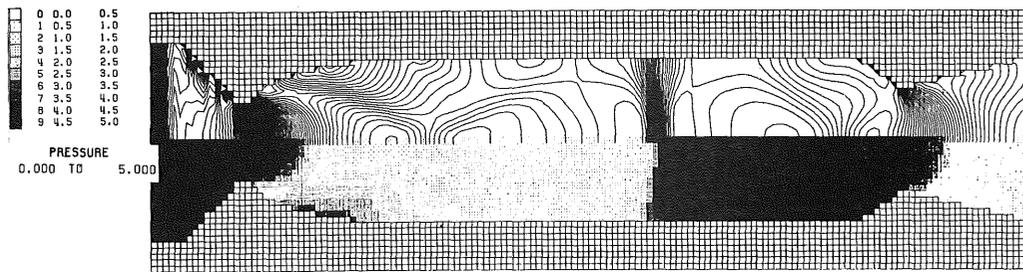
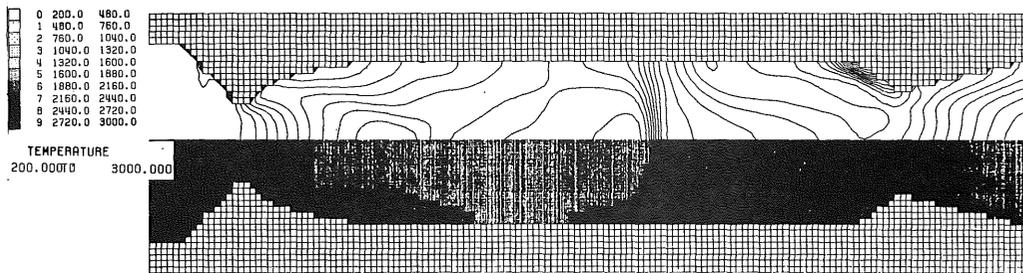
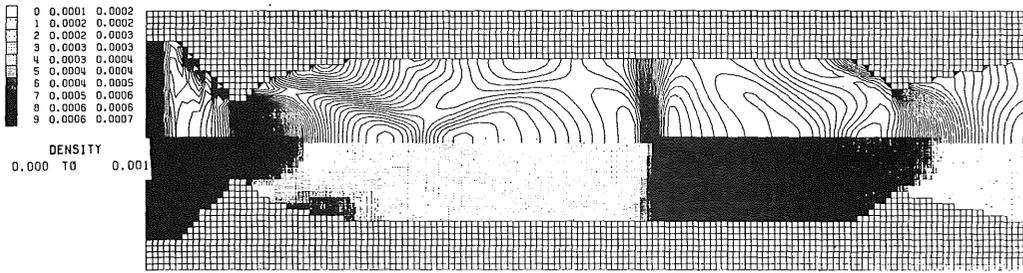


Figure C.20a Wind Tunnel Analysis

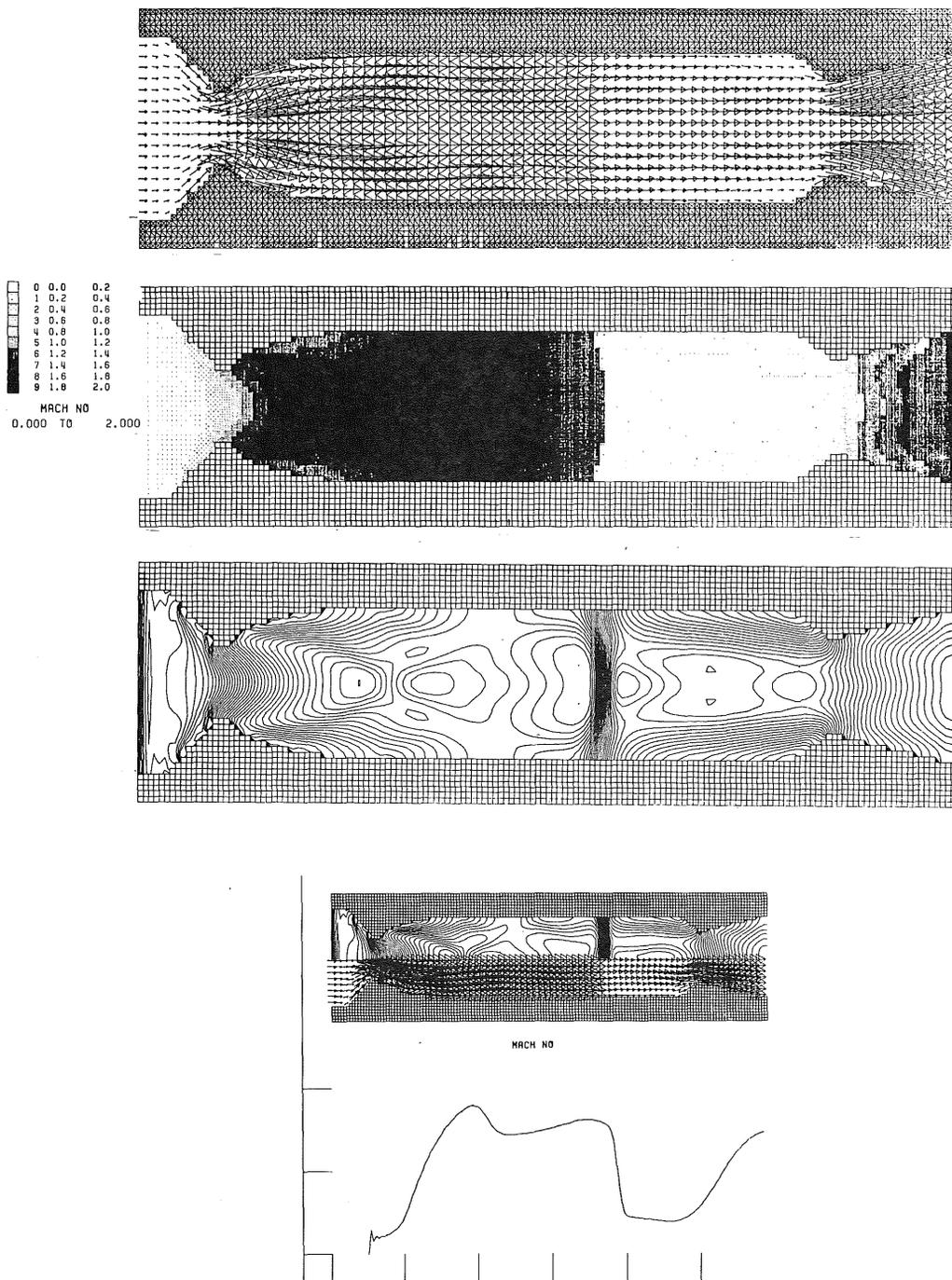
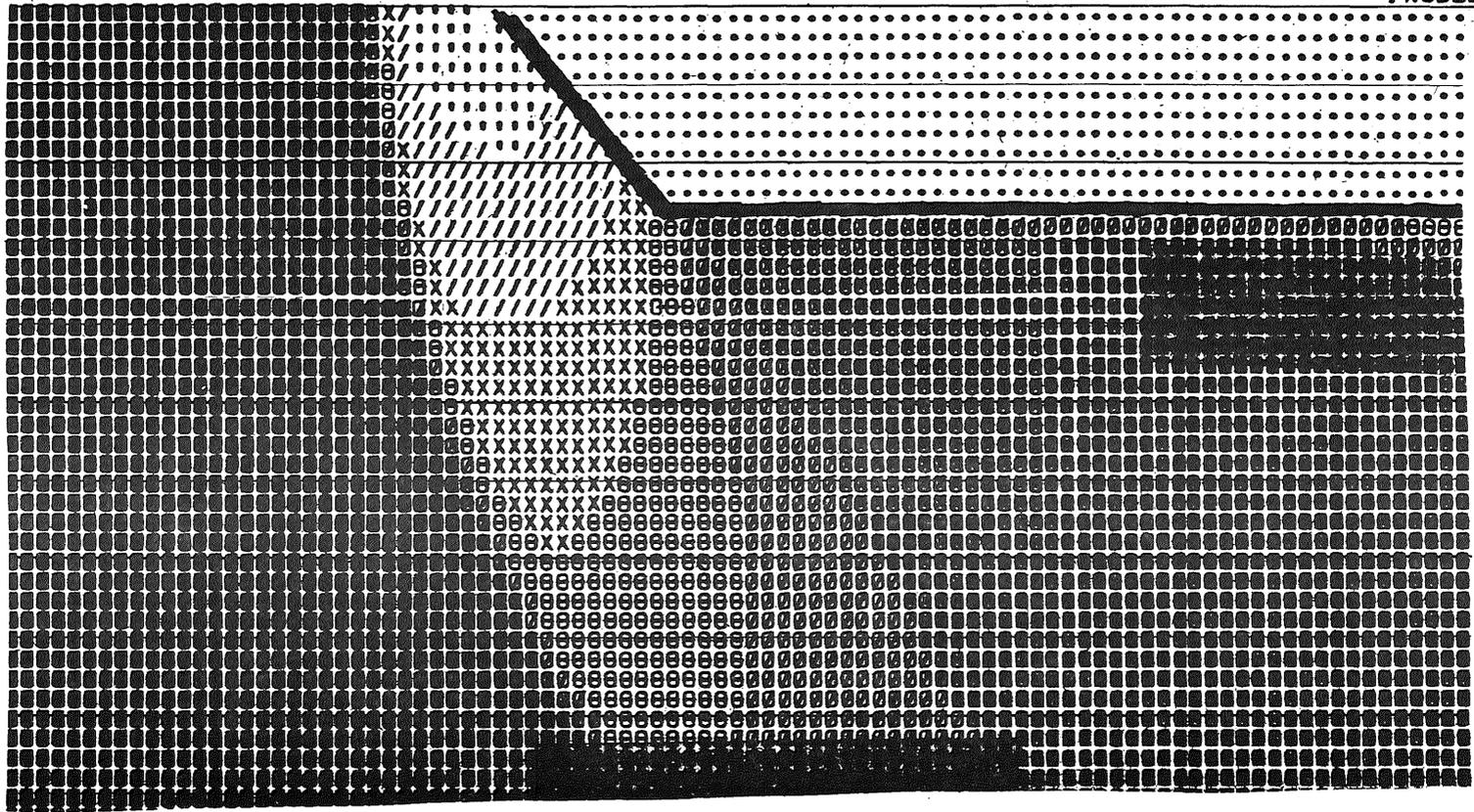


Figure C.20b Wind Tunnel Analysis

MACH NO MIN 0.0 MAX 0.2453E 01 DMLS

•/X000000



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Figure C.21 Digital Plot of Flow Over Sharp-Nosed Projectile

MACH NO

MIN 0.0

MAX 0.3984E 01

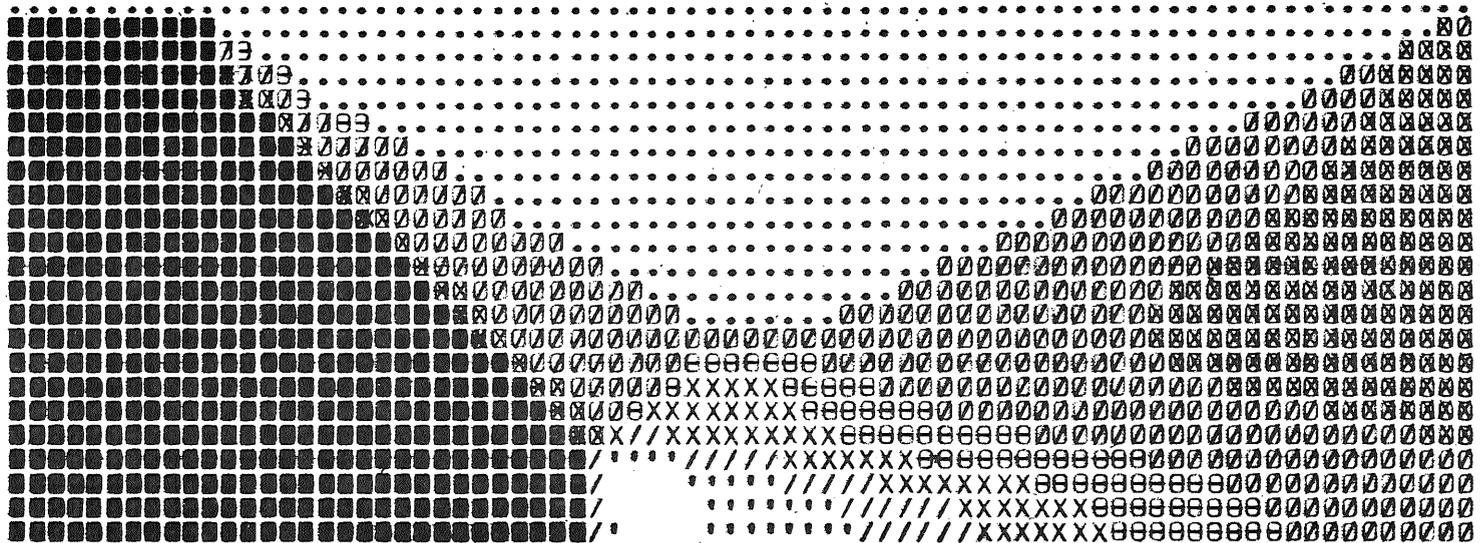


Figure C.22 Digital Plot of Mach Stem

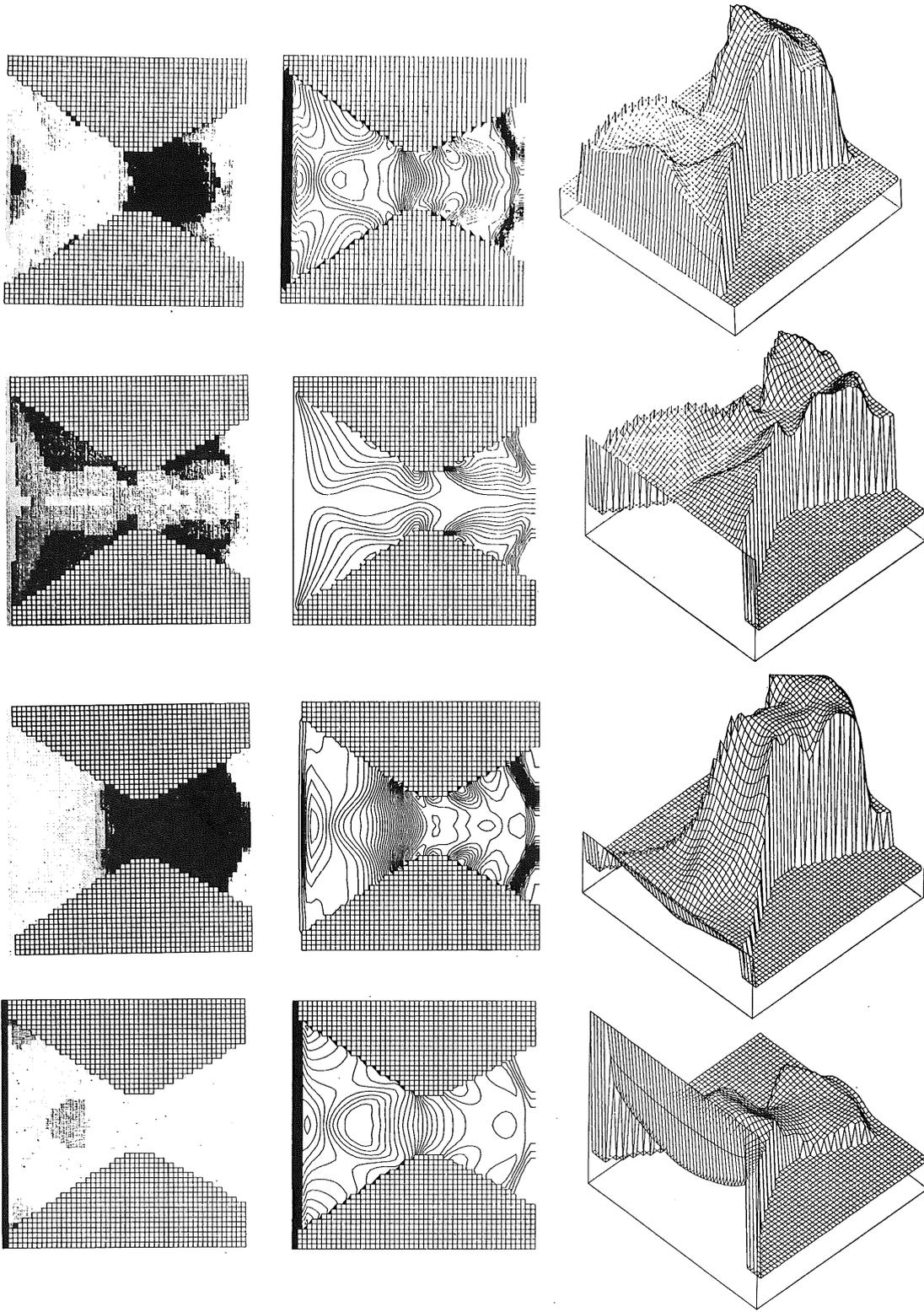
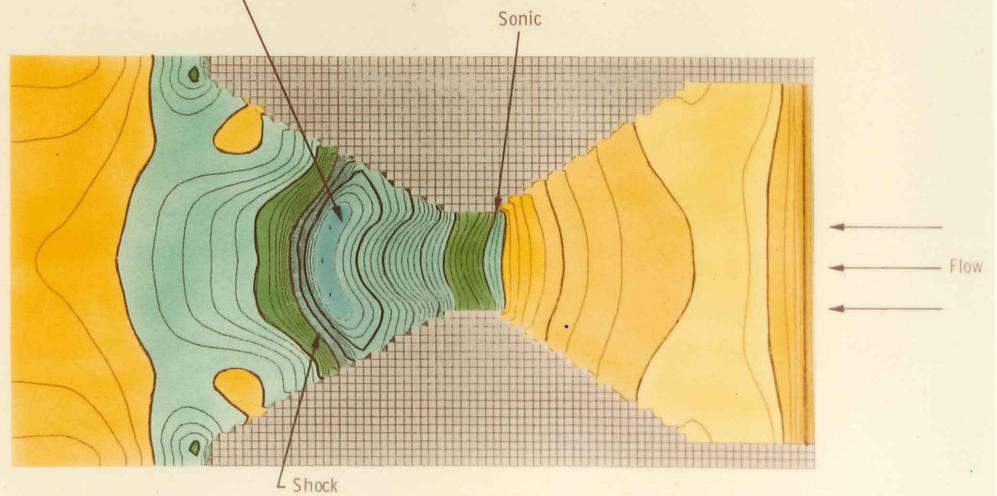
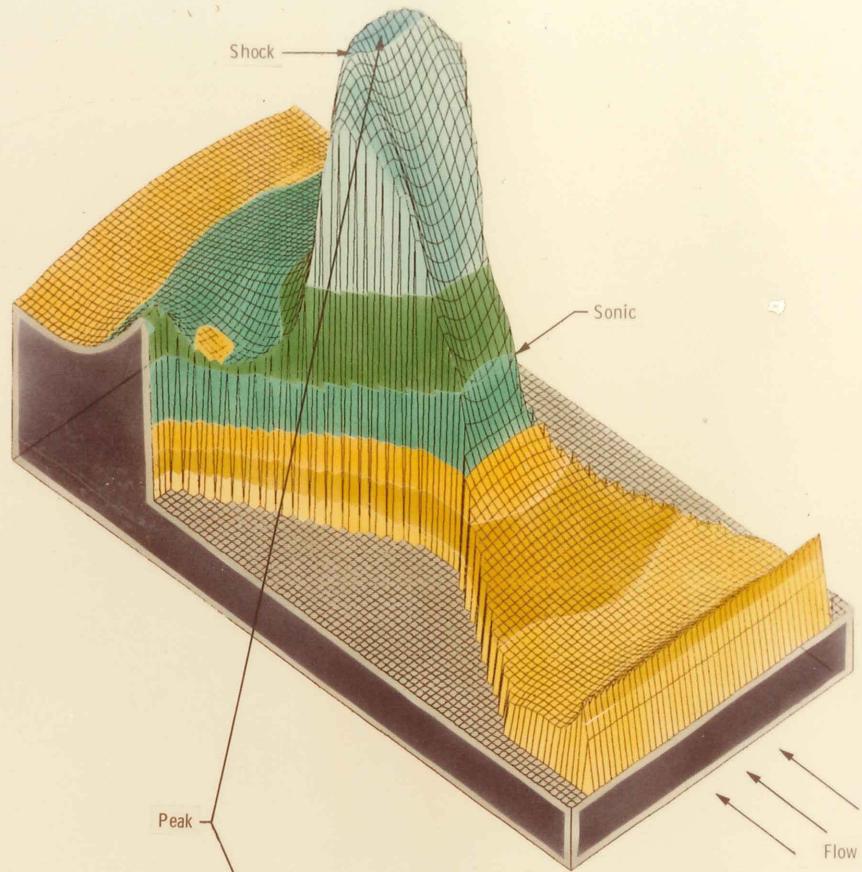


Figure C.23 Pressure, Temperature, Mach Number and Density in a Nozzle



Contour mapping alone does not provide information relating to the gradient direction. However, supplementing these maps with a 3-D perspective, the peaks and valleys become apparent. Color is used in this figure to emphasize regions of similar Mach number.

Figure C.23 Continued

blank page

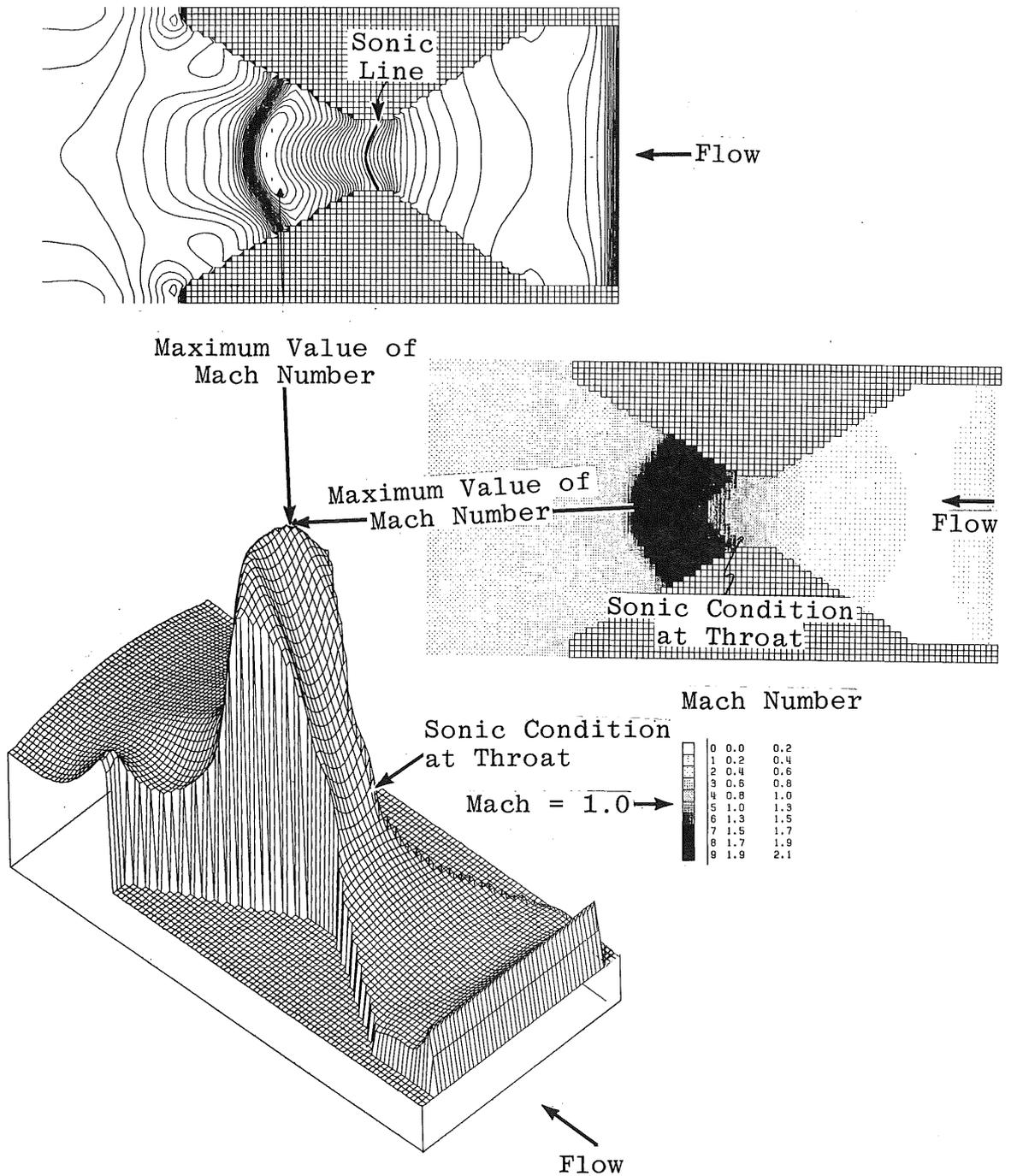


Figure C.23 Continued

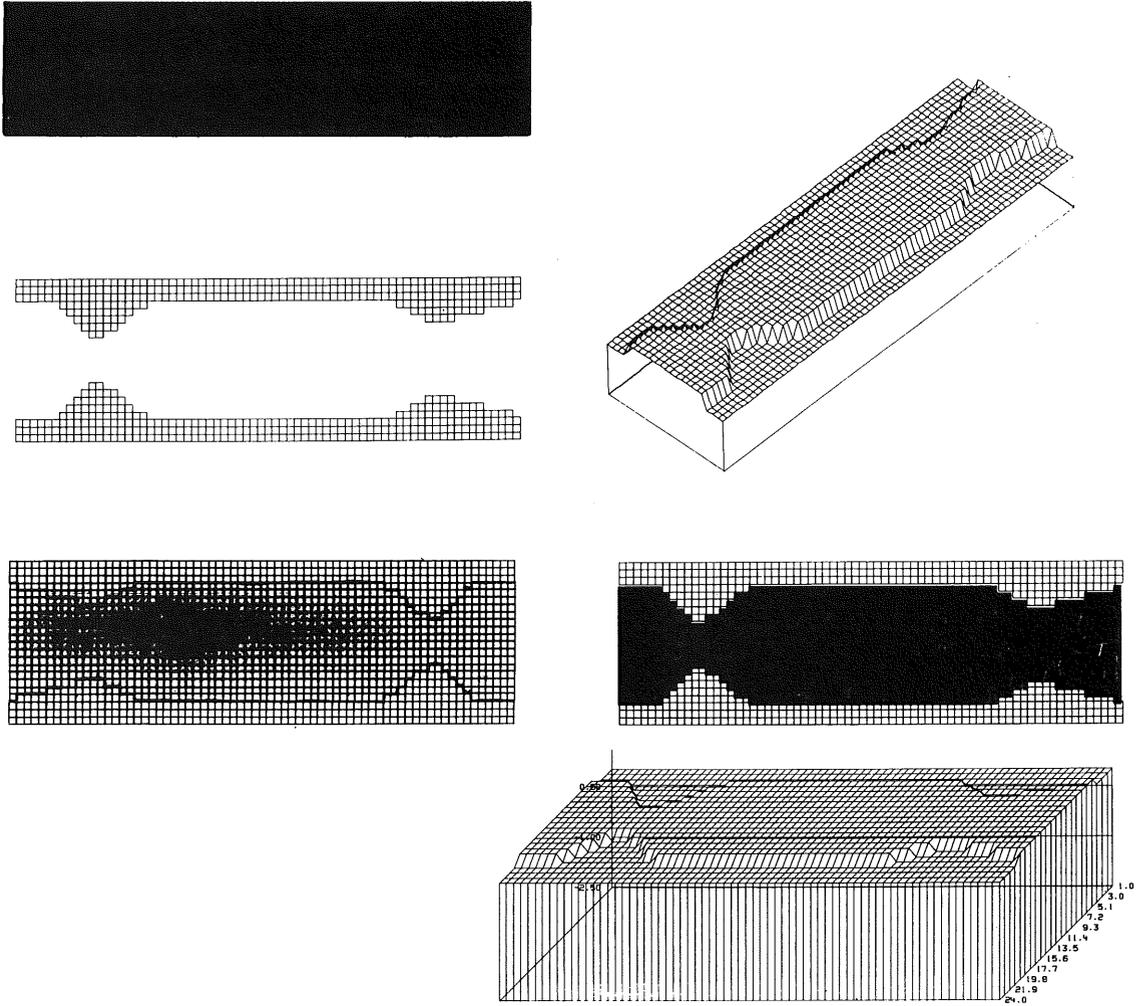


Figure C.24 MHD Generator Grid

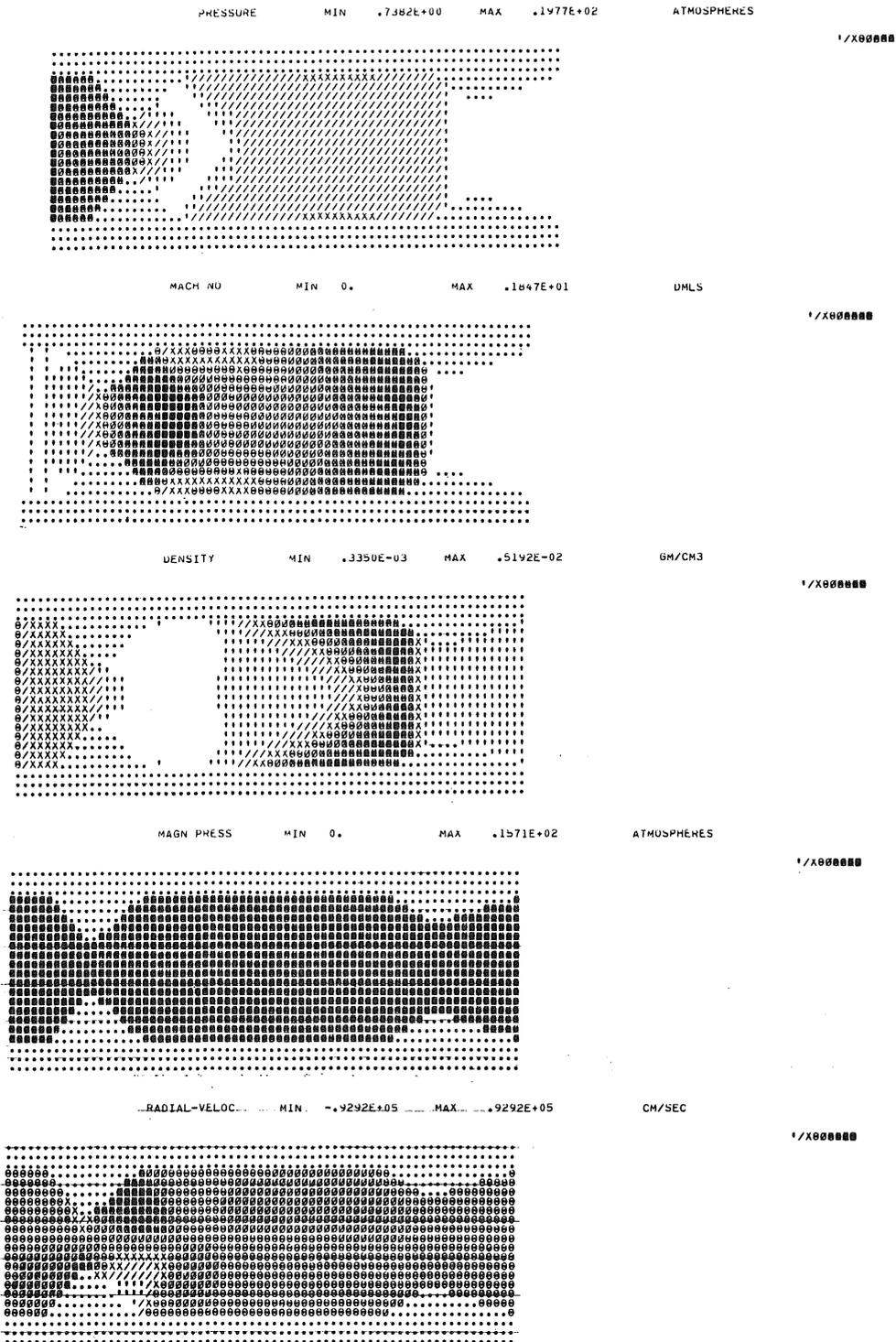


Figure C.25 Digital Plot of MHD Generator Variables

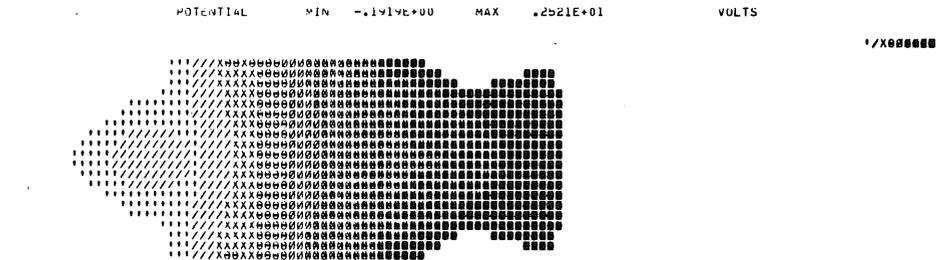
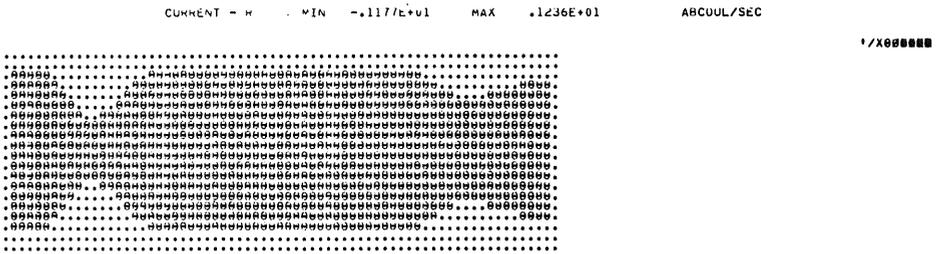
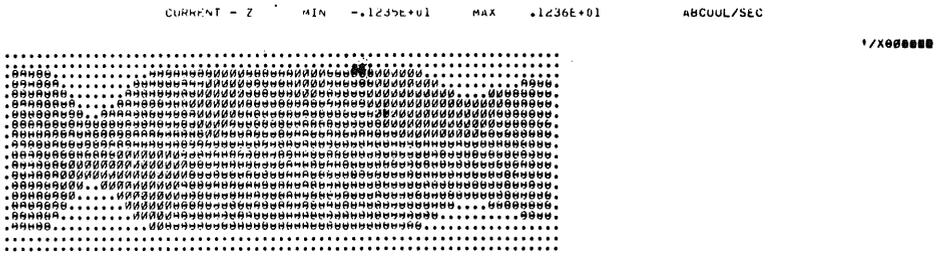


Figure C.25 Continued

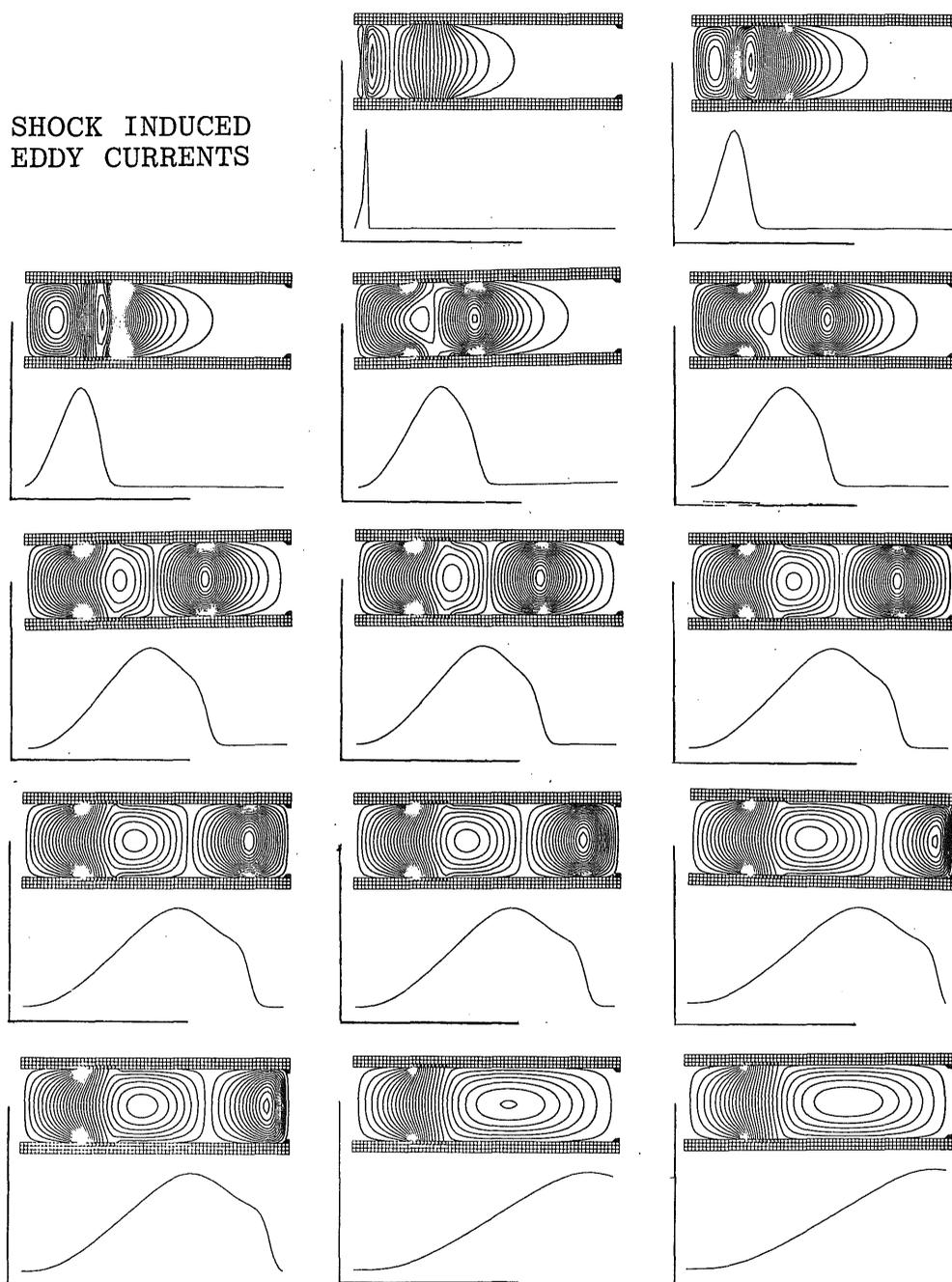
SHOCK INDUCED
EDDY CURRENTS

Figure C.26 Eddy Currents in an MHD Channel,
Induced by a Shock (16-mm Computer
Movie)

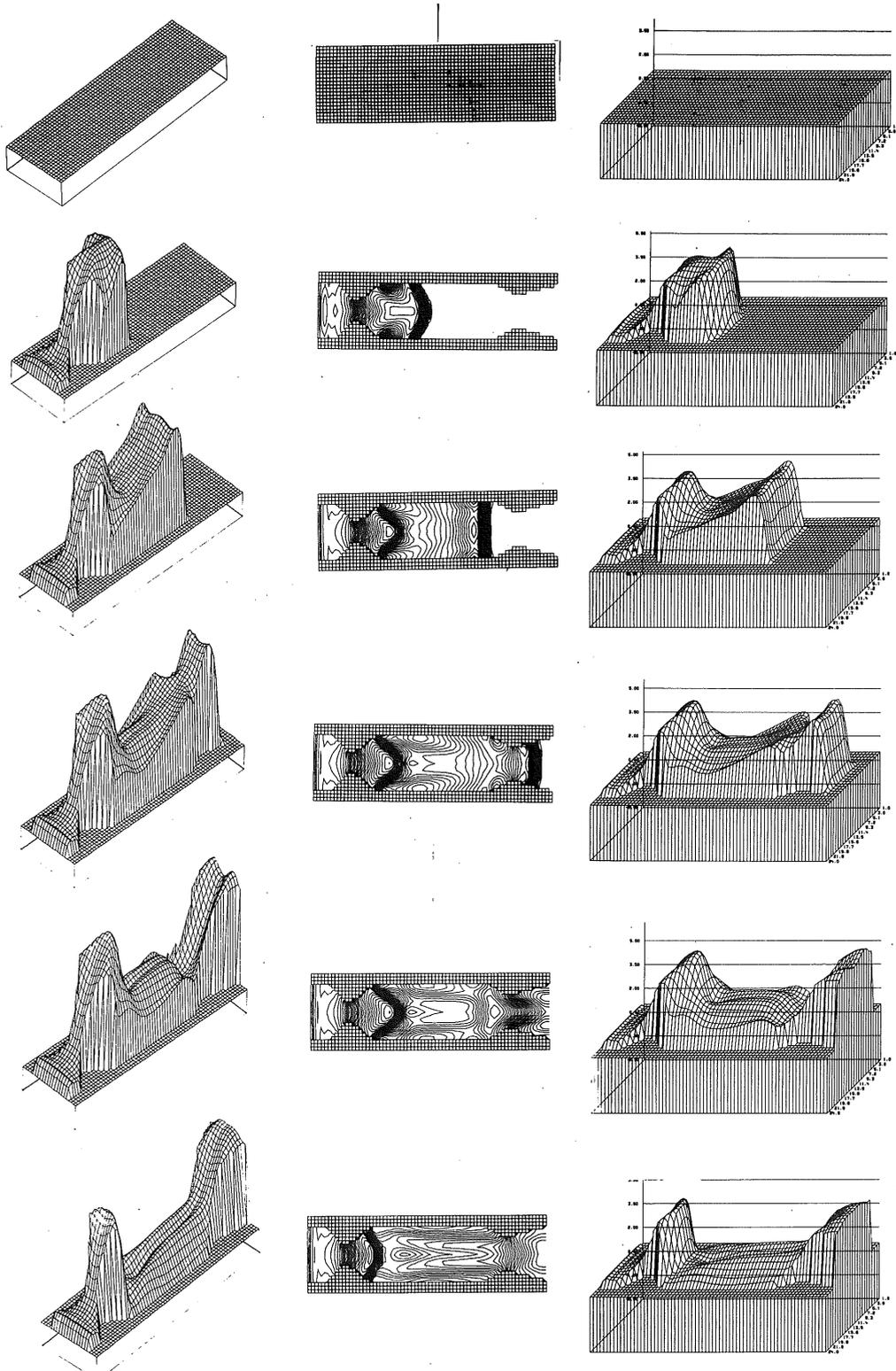


Figure C.27 Transient Pressure Distribution
(16-mm Computer Movie)

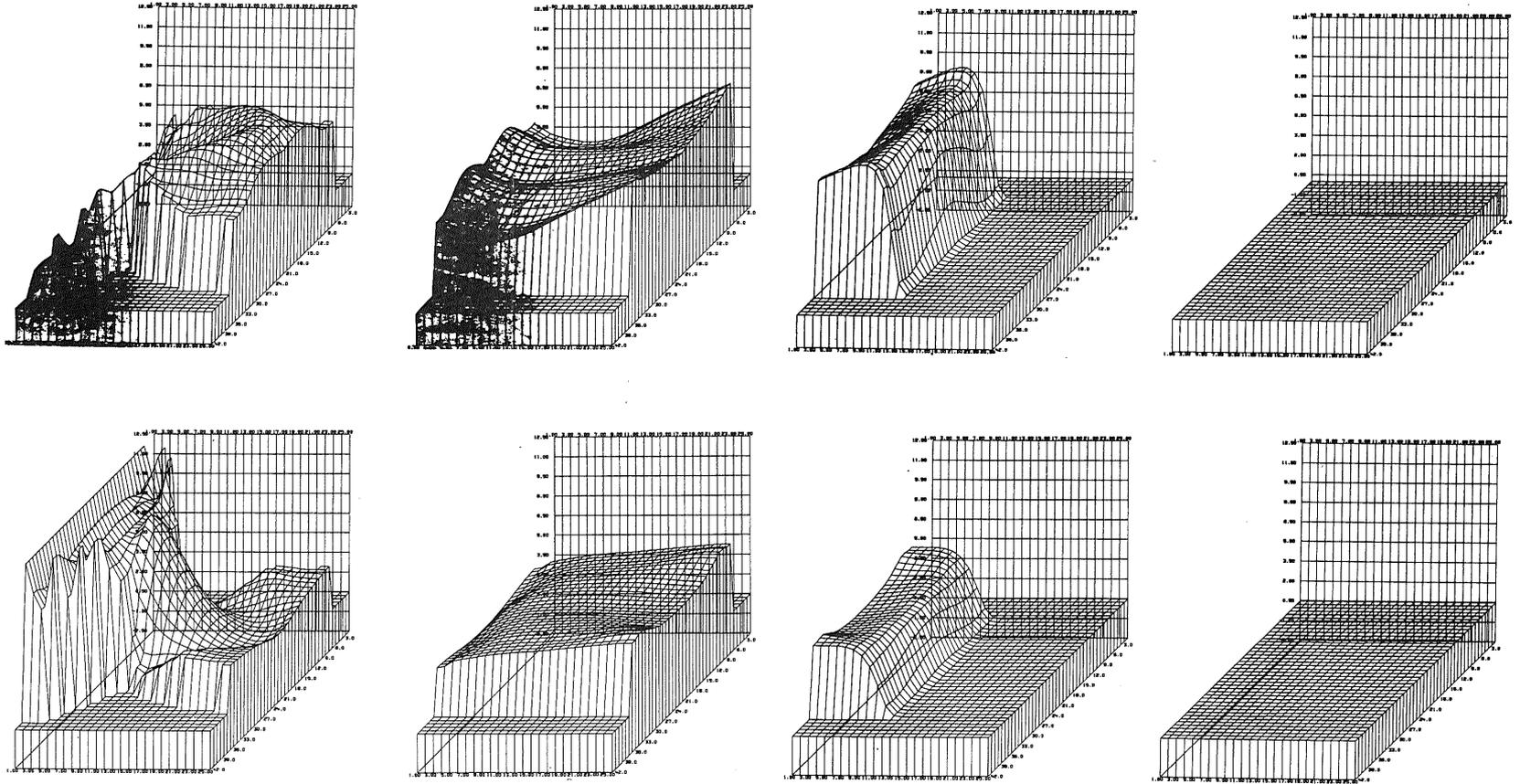


Figure C.28 Sectional View of 3-D Plot

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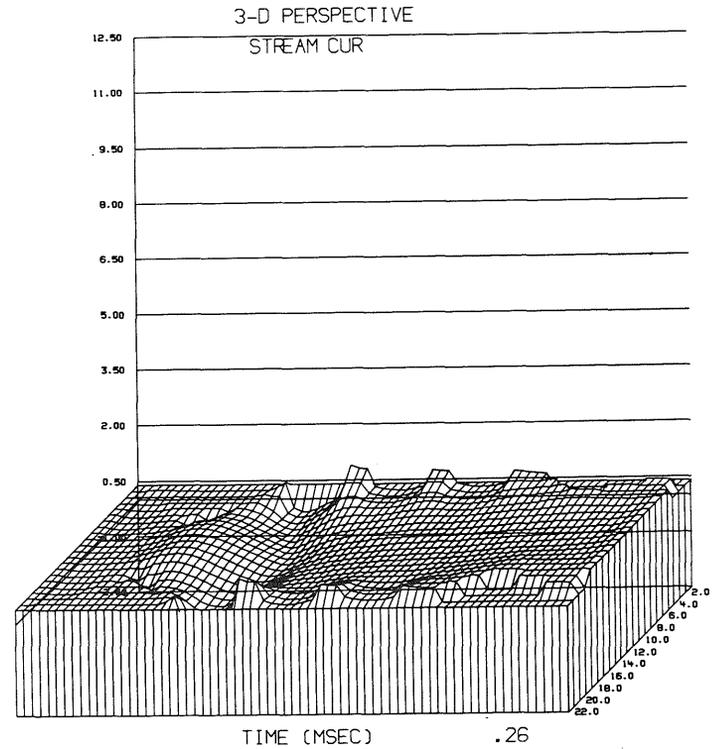
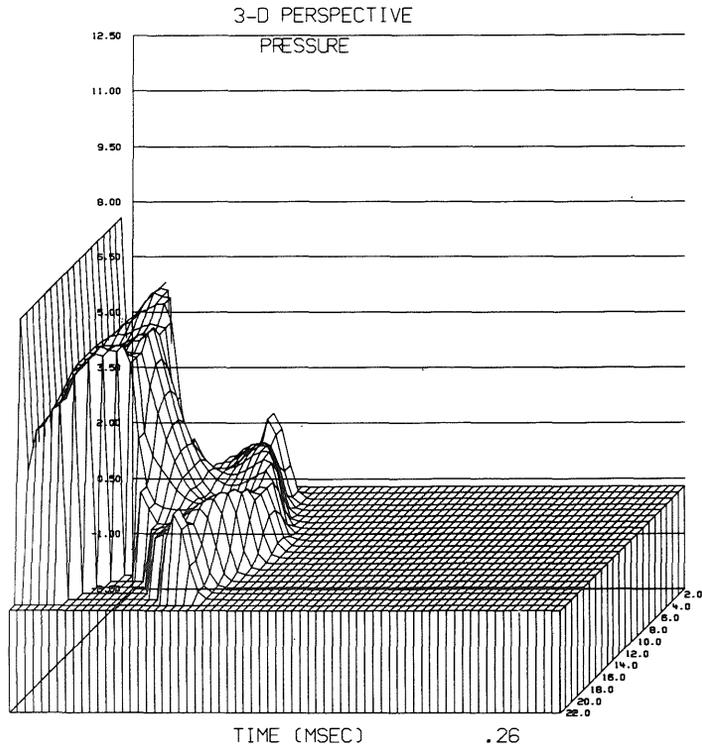
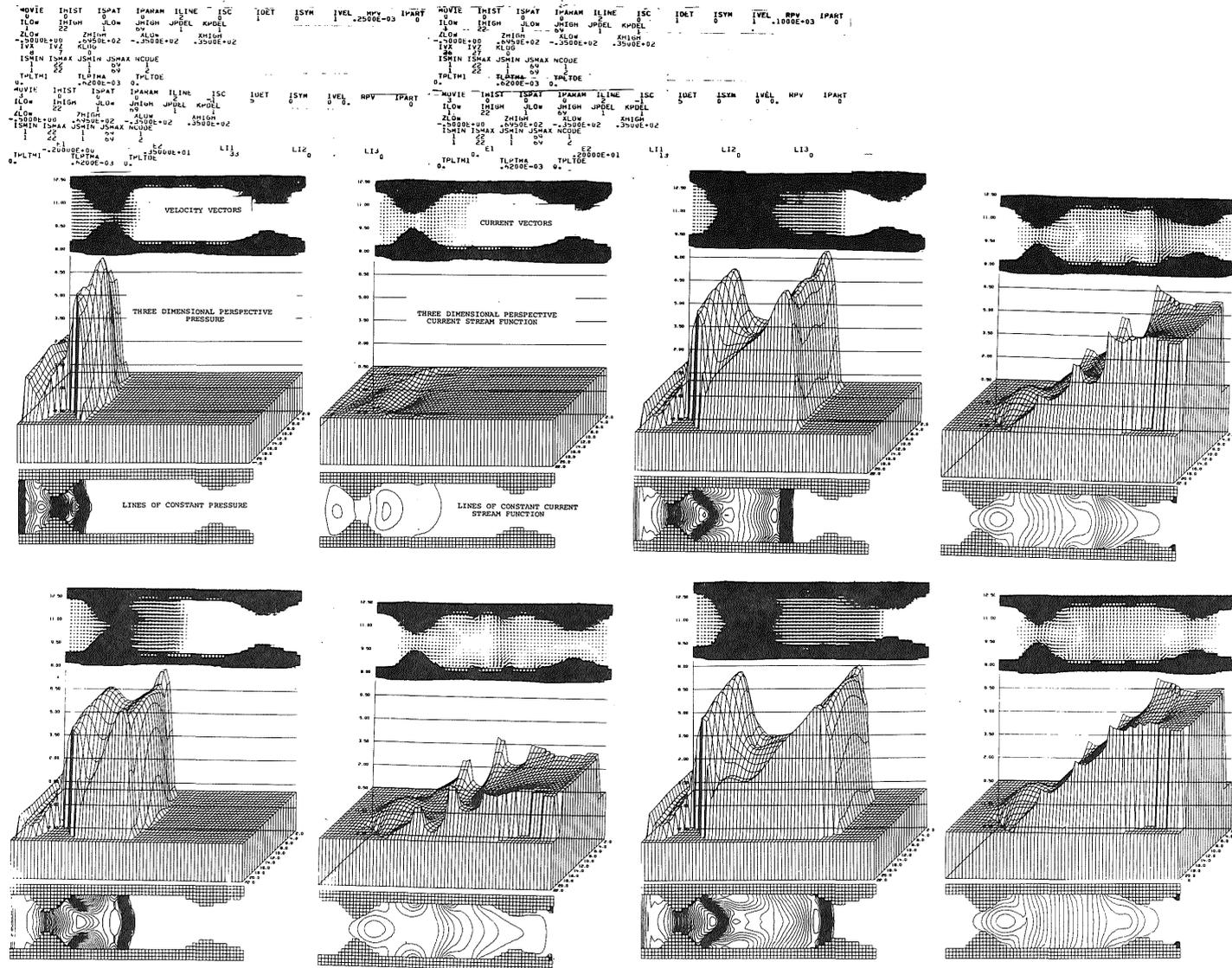


Figure C.29 Initial 3-D Distributions of Pressure and Current Stream Functions (16-mm Computer Movie)



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Figure C.30 Transient Calculation of P and ψ (16-mm Computer Movie)

C.5 TEST CASES

This section contains a list of card inputs for approximately 20 "test cases" which were used to develop the numerical solutions presented in this report. A list of these cases and their central processor execution times follows.

<u>Title</u>	<u>Location</u>	<u>Cycles</u>	<u>CP⁺ Minutes</u>	<u>Grid</u>
1. Flat Plate	Auburn	300	65	25 x 150
2. MHD Generator-Inviscid	Auburn	200	41	20 x 150
3. Simple Nozzle	Auburn	100	21	48 x 48
4. SOR	Auburn	10	4	14 x 40
5. Inviscid Nozzle Flow	Auburn	50	15	48 x 98
6. Couette MHD	Auburn	2500	12	9 x 3
7. Shock Tube (Theta-Field)	AEDC	200	4	10 x 97
8. Turbulence	AEDC	200	4	25 x 50
9. M-117	Auburn	25	87	100 x 300
10. Nozzle Flow	Auburn	250	35	25 x 80
11. Ablated RV*	AEDC	20000	127	50 x 100
12. Nozzle Choking/Shocks*	AEDC	2000	109	25 x 80
13. Shock Induced Eddies*	AEDC	200	238	24 x 70
14. Sonic Line	AEDC	1000	71	50 x 110
15. 3 Electrodes	AEDC	100	6	30 x 103
16. Nozzle Flow	AEDC	200	4	25 x 49
17. One Electrode (Beta = 5)*	AEDC	75	13	24 x 40
18. Projectile	AEDC	800	91	50 x 110
19. Re-Entry Vehicle (M = 22)	AEDC	250	40	50 x 150
20. Viscous Diffusion	AEDC	100	8 sec	9 x 3
21. Couette Flow	AEDC	260	15 sec	9 x 3
22. Thermal Couette	AEDC	1100	1	9 x 3
23. Sound Wave	AEDC	200	5	14 x 40
24. MHD Generator	Eglin	1000	200	42 x 98

Auburn Computer: IBM 370 (5/1)⁺

AEDC Computer: IBM 370 158

Eglin Computer: CDC 6600

⁺CP Time Based on CDC 6600

*Generated Movie → CP Time Predominately for Graphic Commands

REGULAR-IRREGULAR(MACH) REFLECT

44	150	0	0	-1	0	-1	1	1	1	0	1	4	
4.5		1.9		1.8		7.1		1.8		8.5		4.5	15.
10	15	15	2	1	10								
0.1000E	000.1000E	00-.5000E-01	-	.5000E-010.0						0.1000E	010.7500E	00	
0.00128	0.	0.		0.		0.1956E	10						
0.	1.		29.			0.							
	1	1	46	1									
0.0067		100000.		0.		0.6125E	10						
0.		1.											

3	0	0	0	2	-1	1	0	0	0.
1	46	1	85	1	46	1	152		
2.		6.		0.		4.			
1	46	1	152	1					
1	46	1	152	2					
0.		50.				9			
0.		1.		1.		1.			
3	0	0	0	2	-1	0	0	0	0.
1	46	1	152						
1.		8.5		-1.0		6.5			
1	46	1	152	1					
1	46	1	152	2					
0.		50.				9			
0.		1.		1.		1.			
0	0	2	0	2					
1	46	1	152						
-12.5		27.5		-30.		10.			
1	46	1	152	1					
1	46	1	152	2					
1	1	1	152	9					
1	1	1	152	13					
0.		1.							
0	0	0	0	2	0	0	0	1	0.00015
1	46	1	152					3	2
-0.5		7.5		-1.5		6.5			
8		7							
1	46	1	152	1					
1	46	1	152	2					
0.		1.		1.		1.			
0	0	0	0	2	-1	0	0	0	0.
1	46	1	152						
1.0		8.5		-1.0		6.5			
1	46	1	152	1					
1	46	1	152	2					
0.95		16.5				9			
0.		1.		1.		1.			
0	0	0	0	2	-1	0	0	0	0.
1	46	1	152						
1.0		8.5		-1.0		6.5			
1	46	1	152	1					
1	46	1	152	2					
0.1		3.9				13			
0.		1.		1.		1.			
0	0	0	0	2		1			1
1	46	1	152						
0.5		8.5		-2.5		5.5			
2	20	10	10	3					
1	46	1	152	1					
1	46	1	152	2					
0.		1.		1.		1.			

M-117 SUBSONIC

100	300	1	50	1	0	-1	1	1	1	0	1	15	0
0.	0.		-0.12		0.1		-0.21		0.2		-0.28		0.3
-0.34	0.4		-0.39		0.5		-0.43		0.6		-0.46		0.7
-0.48	0.8		-0.49		0.9		-0.495		1.		-0.498		1.1
-0.5	1.2		-0.5		2.4		0.		6.				
1	15	15	1	0	-1								
0.06		0.0333333	-6.060		-3.37995	0.			1.		0.75		
0.001314	0.		0.		0.2406E 10								
1.	1.		29.		0.								
1	1	102	302										
0.001314	15000.		0.		0.1956E 10								
1.	1.												

0	0	0	0	2	-1	0	2	0	0.0010
1	102	75	225	1	102	1	302		
-10.		-2.		-4.		4.			
1	102	1	302	1					
1	102	1	302	2					
0.89		0.97			9			1	
0.		1.		1.	1.				
0	0	0	0	2	0	0	2	1	0.0010
1	102	1	302					3	3
-10.		-2.		-4.		4.			
8		7							
1	102	1	302	1					
1	102	1	302	2					
0.		1.		1.		1.			
3	0	0	0	2	-1	0	2	0	0.0010
1	102	1	302						
-10.		2.		-6.		6.			
1	102	1	302	1					
1	102	1	302	2					
0.91		0.95			9				
0.		1.		1.	1.				
3	0	0	0	2	-1	0	2	0	0.0010
1	102	1	302						
-10.		-4.		-3.		3.			
1	102	1	302	1					
1	102	1	302	2					
-0.75		0.25			17				
0.		1.		1.	1.				
3	0	0	0	2	-1	0	2	0	0.0010
1	102	1	302						
-10.		-4.		-3.		3.			
1	102	1	302	1					
1	102	1	302	2					
0.42		0.47			13			1	
0.		1.		1.	1.				

```

THERMAL DIFFUSION
  9   3   0   1   0   1   1
 10  1   2 500 1 100
1.0   .2   0.   -1.1   .01   .01   .75
1.   1.   29.   100.
0.   1.   0.
1.   1   1   1   5   200.
0.   1.
11  1  11  5   200.
1.
0.   1.

```

```

FUNCTION COND(K,J,IHALF,JHALF)
COMMON /V14/ NMAGN,NTHRM,NVISC,NCONV,IPDT
NTHRM=1
COND=1.
RETURN
END
FUNCTION CV(K,J,KHALF,JHALF)
CV=1.
RETURN
END
SUBROUTINE HULLP1
RETURN
END
SUBROUTINE HULLP2
RETURN
END
} Subroutines
  "Dummied" Out

```

```

MAGNETIC DIFFUSION
  9   3   0   1   0   1   1
 10  1   2 500 1 100
1.0   .2   0.   -1.1   .01   .01   .75
1.   0.   0.   1.
0.   .0796 29.   0.   100.
1.   1   1   1   5   200.
0.   .0796   1.
11  1  11  5   200.
1.
0.   .0796   1.

```

```

SUBROUTINE HULLP1
RETURN
END
SUBROUTINE HULLP2
RETURN
END
} Subroutines
  "Dummied" Out
FUNCTION SIG(K,J,KHALF,JHALF,KJ)
COMMON /V14/ NMAGN,NTHRM,NVISC,NCONV,IPDT
SIG=1.
NMAGN=1
RETURN
END

```

NOTE: Labelled Common Blocks V1 to V32 have since been renamed: CARRAY, COUTP, CMESH, CBOUND, etc.

```

VISCOUS DIFFUSION
  9      3      0      1      0      1      1      -2
1.7     0.     1.7   10.
10     1  2  50   100  -1.1   .01   .01   .75
1.0    .2     0.    0.1929E 10
1.     100.    0.    0.
1.     1.     29.    0.
1.     1  1  1  5    0.1929E 10
1.     200.   0.
1.     1.
1.     11  1  11  5    0.1929E 10
1.     200.   0.
1.     1.

```

```

FUNCTION GAMM(I,J)
GAMM=1.
RETURN
END

```

```

          SOUND WAVE
    14  40  0  0 -1  0 -1 -1  1  1  1  0  0
    40  10  2  10  1  100
1.     1.     -0.5   -0.5  0.     1.     0.75  0.
0.001  0.     0.     0.1956E 10
0.     1.     29.    0.
0.0011 1  16  1  0.1956E 10
0.     1.

```

```

    0  0  1  0  2
    1  16  1  42
-1.   7.   -2.5  5.5
    1  16  1  42  1
    1  16  1  42  2
    1  1  1  42  9
0.000001 1.
    0  0  1  0  2
    1  16  1  42
-1.   7.   -2.5  5.5
    1  16  1  42  1
    1  16  1  42  2
    1  1  1  42  9
0.     0.0000001
    0  0  1  0  2
    1  16  1  42
-1.   7.   -2.5  5.5
    1  16  1  42  1
    1  16  1  42  2
    1  1  1  42  9  1
0.     1.0

```

```

BLASIUS FLAT PLATE (RE=2500)
 25 150 1 0 1 1 1 0 1 -2
0.048 0. 0.048 0.4
 50 1 8 50 1 250
0.002 0.002 -0.001 -0.001 0.000001 0.000001 1.
0.001 .1929 E 10
0.0001 1. 29. 0.
 1 1 27 152
0.001 833.33 .19290E 10
0.0001 1.

```

```

 0 0 0 0 2 0 1 0 1 125.
 1 22 1 42 10 1
-1. 5. -1. 5.
 8 7
 1 22 1 42 1
 1 22 1 42 2
0. 1. 1. 1.

```

```

TURBULENT JET
 25 50 0 1 0 1 0 1 2
100 1 10 200 1 200
0.01 0.005 -0.005 -0.0650 .00001 .00001 1.
0.0023 1.0
0.0023 1. 29.
 14 1 27 52
0.0023 1.0 1.5
0.0023 1.

```

```

 3 0 0 0 2 -1 0 0
 1 27 1 52
-0.05 0.20 -0.125 0.125
 1 27 1 52 1
 1 27 1 52 2
-0.1 1.1 7
0. 1. 1.
 0 0 0 0 2 0 1 0 1 125.
 1 27 1 52 5 1
-0.05 0.20 -0.125 0.125
 8 7
 1 27 1 52 1
 1 27 1 52 2
0. 1. 1. 1.
 0 0 0 0 2 -1 0 0
 1 27 1 52
-0.15 0.10 -0.125 0.125
 1 27 1 52 1
 1 27 1 52 2
0.01 0.99 7
0. 1. 1. 1.

```

```

FUNCTION EDDY (I,J)
COMMON /V1/ R(52),Z(152),DR(52),DZ(152),U(52,152),V(52,152),
1E(52,152),RHO(52,152),B(52,152)
REAL R#8
U1=1.0
EDDY=0.014*0.098*Z(J)*U1
RETURN
END

```

```

FUNCTION GAMM(I,J)
GAMM=1.0
RETURN
END

```

```

COUETTE FLOW
  9   3   1   1   0   1
100  1  1 100 1000
1.    .2          .0100   .0125   1.
0.0023          .1929 E 10
0.0023  1.    29.    0.
  1   1   1   5
0.0023          .1929 E 10
0.0023  1.
  11  1  11  5
0.0023  1.    .1929 E 10
0.0023  1.

```

```

FUNCTION GAMM(I,J)
GAMM=1.1
RETURN
END
SUBROUTINE SPEC
COMMON /V1/ R(16),Z(042),DR(16),DZ(042),U(16,042),V(16,042),
1E(16,042),RHO(16,042),B(16,042)
COMMON /V4/ KMAX,JMAX,KP1,JP1,KP2,JP2,IAXI,ITURB,ISYM(4)
EO=1000.
P=-5.*P
DO 1 J=1,JP2
DO 1 K=1,KP2
CJ=J
RHO(K,J)=0.0023
V(K,J)=0.
E(K,J)=CJ*P+EO
1 CONTINUE
RETURN
END

```

```

COUETTE FLOW WITH HEAT TRANSFER
  9   3   1   1   0   1
1000  1  1 100 1000
1.    0.1        -0.05   .0050   .0050   1.
0.0023          1.0
0.0023  1.    29.    0.
  1   1   1   5
0.0023          1.
0.0023  1.
  11  1  11  5
0.0023  1.    1.5
0.0023  1.

```

```

  1   12  1   5   2
-110. 290. -350. 50.
  1  12  1   5   1
  1  12  1   5   2
  1  12  4   4   7
0.    1.    1.    1.

```

```

FUNCTION GAMM(I,J)
COMMON /V2/ VISC
DATA IKT/0/
GAMM=1.0

```

```

RETURN
END
SUBROUTINE SPEC
COMMON /V1/ R(16),Z(042),DR(16),DZ(042),U(16,042),V(16,042),
1E(16,042),RHO(16,042),B(16,042)
COMMON /V4/ KMAX,JMAX,KP1,JP1,KP2,JP2,IXI,ITURB,ISYM(4)
DD 1 J=1,JP2
DD 1 K=1,KP2
CJ=J
RHO(K,J)=0.0023
V(K,J)=0.
1 CONTINUE
RETURN
END
FUNCTION COND(K,J,IHALF,JHALF)
COMMON /V14/ NMAGN,NTHRM,NVISC,NCONV,IPOT
NTHRM=1
COND=1./8.*0.0023
RETURN
END
FUNCTION CV(K,J,KHALF,JHALF)
CV=1.
RETURN
END

COUETTE MHD
      9      3      1      1      1      0      4
250      1      1 500      2500
1.      .2      .0005      .0005      0.05
1.0      1.      29.      .1929 E 10      2.
1.0      1      1      5      .1929 E 10      2.
1.0      1.
1.0      11      1      11      5      .1929 E 10      2.
1.0      0.
1.0      1.
      1      1      2
1      12      1      5      2
-110.      290.      -350.      50.
1      12      1      5      1
1      12      1      5      2
1      12      4      4      7
0.      1.      1.      1.
SUBROUTINE SPEC
COMMON /V1/ R(52),Z(152),DR(52),DZ(152),U(52,152),V(52,152),
1E(52,152),RHO(52,152),B(52,152)
COMMON /V4/ KMAX,JMAX,KP1,JP1,KP2,JP2,IXI,ITURB,ISYM(4)
COMMON /V6/ TIME,DT,NCYCLE,NMAX,MINDT,MAXDT
COMMON /V23/ BR(52,177),BZ(52,177)
REAL R*8
DD 1 J=1,JP2
BZ(11,J)=0.
BZ(1,J)=BZ(2,J)
1 CONTINUE
RETURN
END
FUNCTION SIG(I,J,K,L,M)
COMMON /V14/ NMAGN,NTHRM,NVISC,NCONV,IPOT
SIG=1.0
NMAGN=1
RETURN
END
FUNCTION GAMM(I,J)
GAMM=1.0
RETURN
END

```

SHOCK TUBE (NO FIELDS)

4.	3	97	0	0	-1	1	-1	1	1	1	0	0	2
	200	2	3	200	1	200	100.						
1.0		0.1		0.		0.		.00000001	.1		.75		0.
0.01314						0.		0.1957E	10				
0.		1.		29.		0.							
	1	1	5	48									
0.01314								0.1957E	10				
0.		1.											
	1	49	5	99									
0.001314								0.1957E	10				
0.		1.											

	0	0	6	0	2			2	0		.001
	1	5	1	99				3	2		
-1.		99.		-70.		30.					
	1	5	1	99	1						
	1	5	1	99	2						
	2	2	1	99	7						
	2	2	1	99	9						
	2	2	1	99	11						
	2	2	1	99	13						
	2	2	1	99	14						
	2	2	1	99	16						
0.		1.		0.		0.					

SHOCK TUBE (THETA FIELD)

	3	97	0	0	-1	1	-1	1	1	1	3	0	0
	200	2	3	200	1	200							
1.0		0.1		0.		0.		.00000001	.1		.35		0.
0.01314						0.		0.1957E	1010000.				
0.		1.		29.		0.							
	1	1	5	48									
0.01314								0.1957E	1010000.				
0.		1.											
	1	49	5	99									
0.001314								0.1957E	1010000.				
0.		1.											

	0	0	0	0	2	-1	2	0	0		.001
	1	12	1	99				3	2		
-1.		99.		-70.		30.					
	1	12	1	99	1						
	1	12	1	99	2						
6500.		12500.				16					
0.		1.		1.		1.					
	0	0	6	0	2			2	0		.001
	1	5	1	99				3	2		
-1.		99.		-70.		30.					
	1	5	1	99	1						
	1	5	1	99	2						
	2	2	1	99	7						
	2	2	1	99	9						
	2	2	1	99	11						
	2	2	1	99	13						
	2	2	1	99	14						
	2	2	1	99	16						
0.		1.		1.		1.					

ABLATED RE-ENTRY VEHICLE

50	100		0	-1	1	1	1	1	0	1	16	
-38.	0.		-38.0	1.		-37.	1.5		-28.		5.	
-26.	6.		-24.	7.5		-23.	8.3		-22.		9.5	
-21.	11.		-20.	12.8		-19.	15.		-18.		17.4	
-17.	19.		-16.	20.		-15.	20.6		0.		22.0	
500	5	5	50	1	1500							
1.00	1.00		-0.5		-51.50	0.		1.		0.75		
0.00134					.1929 E 10							
0.	1.		29.		0.							
1	1	1	102									
0.00268	0.000		300000.		4.6929E 10							
0.	1.											

3	0	0	0	2	-1	0	1	1		.00015	
1	52	1	102								
-60.	10.		-50.		0.						
8	7										
1	52	1	102	1							
1	52	1	102	2							
0.	200.				9				1		
0.	1.										
3	0	0	0	2	-1	0	1	0		.00015	
1	52	1	102								
-60.	10.		-50.		0.						
1	52	1	102	1							
1	52	1	102	2							
0.	9.				13.						
0.	1.		1.		1.						
0	0	0	0	2	-1	0	1	0		.00015	
1	52	1	102								
-60.	10.		-50.		0.						
1	52	1	102	1							
1	52	1	102	2							
0.	4100.				31						
0.	1.										
3	0	0	0	2	-1	0	1	0		.00015	
1	52	1	102								
-60.	10.		-50.		0.						
1	52	1	102	1							
1	52	1	102	2							
0.	4100.				31						
0.	1.								1		
0.	1.		0.		0.						

RE-ENTRY VEHICLE M=22

50	150	0	0	1	0	-1	1	1	1	1	1	-4	
0.	37.		-2.		39.		-6.		43.		-16.		92.
250	10	10	50	1	250								
1.0	1.0		-0.5		-51.5		0.1000E-101.				0.10		
0.0012	0.		0.		0.2000E 10								
100.	1.		29.		0.								
1	1	52	32										
0.0005	1500000.		0.		113.28E 10								
100.	1.												

```

0 0 0 0 2 0 1 2 1 0.000025
1 52 1 152 3 1
-5. 105. -55. 55.
8 7
1 52 1 152 1
1 52 1 152 2
0. 1.
3 0 0 0 2 -1 1 2 0 0.
1 52 1 152
-5. 105. -55. 55.
1 52 1 152 1
1 52 1 152 2
1. 20. 13
0. 1.
3 0 0 0 2 -1 1 2 0 0.
1 52 1 152
-5. 105. -55. 55.
1 52 1 152 1
1 52 1 152 2
0. 1.5000E 07 36
0. 1.
0 0 1 0 2 0 1 0 0 0.00000
1 52 1 152
-50. 200. -125. 125.
1 52 1 152 1
1 52 1 152 2
2 2 1 152 9
0. 1. 0. 0.
0 0 0 0 2 -1 1 2 0 0.
1 52 1 152
-5. 105. -55. 55.
1 52 1 152 1
1 52 1 152 2
1. 20. 13
0. 1.
SUBROUTINE SPEC
COMMON /V1/ R(52),Z(152),DR(52),DZ(152),U(52,152),V(52,152),E(52,
1152),RHO(52,152),B(52,152)
COMMON /V6/ TIME,DT,NCYCLE,NMAX,MINDT,MAXDT
COMMON /V7 / RHOO,VZ,VR,BO,EO,VISCO,PERMO,SIGO,COND0,CVO,VELDC
1,PHIO
COMMON /V15/ STAB,ARFV
COMMON /V25/ DE(52,177), IOBK(202),IOBL(202),DANGLE(202),IDFN
REAL R*8
DATA IKT/0/
IKT=IKT+1
IF(IKT.GT.1) GO TO 5
5 CONTINUE
IF(NCYCLE.GT.100) STAB=0.25
IF(NCYCLE.GT.200) STAB=0.50
IF(NCYCLE.GT.400) STAB=0.75
J=94
DO 1 K=36,52
IF(U(K,J+1).GT.0) GO TO 100
RHO(K,J)=RHO(K,J+1)
U(K,J)=-U(K,J+1)
V(K,J)=V(K,J+1)
E(K,J)=E(K,J+1)
GO TO 1
100 RHO(K,J)=RHOO
U(K,J)=VZ
V(K,J)=VR
E(K,J)=EO
RETURN
END

```

PROJECTILE (1/1)

0.	50	110			1	0	-1	1	1	1	0	0	3
0.	200	5	5	40	1	800	60.	-10.			180.		
1.		1.					-51.5	0.			1.		.75
0.00134							.1929 E 10						
0.		1.		29.			0.						
0.00268	1	1	52	1			.51000E 10						
0.		1.											
0.	0	0	0	0	2	0	1	2	1		.0004		
0.	1	52	1	112					3		1		
0.		100.		-50.		50.							
0.	8	7											
0.	1	52	1	112	1								
0.	1	52	1	112	2								
0.		1.		1.		1.							
0.	3	0	0	0	2	-1	1	2	0		.0015		
0.	1	52	1	112									
0.		100.		-50.		50.							
0.	1	52	1	112	1								
0.	1	52	1	112	2								
0.		2.501				13					1		
0.		1.											
0.	0	0	0	0	2	-1	1	2	0		.0015		
0.	1	52	1	112									
0.		100.		-50.		50.							
0.	1	52	1	112	1								
0.	1	52	1	112	2								
0.		2.501				13					1		
0.		1.		1.		1.							

NOZZLE FLOW

0.6900	25	80	0	0	-1	0	1	1	1	1	0	1	4
0.3333E-010.	125	10	10	250	1	0.2800	0.6		0.6900		1.30	0.69	2.70
.001314					1	250					0.1000E 010.	0.3000E 00	
0.		1.		29.			.19570E+100.						
0.015	1	1	27	1			0.						
0.		1.					.19570E+100.				0.	0.	
0.	0	0	0	0	2	0	0	2	1		0.0015		
-0.5	1	27	1	82					2	2			
0.	8	7											
0.	1	27	1	82	1								
0.	1	27	1	82	2								
0.		1.		1.		1.							
0.	3	0	0	0	2	-1	0	2	0		0.0015		
-0.8	1	27	1	82					2	2			
0.		1.2		-1.		1.							
0.	1	27	1	82	1								
0.	1	27	1	82	2								
0.		2.3				13							
0.		1.		1.		1.							
0.	0	0	0	0	2	-1	0	2					
-0.8	1	27	1	82									
0.		1.2		-1.		1.							
0.	1	27	1	82	1								
0.	1	27	1	82	2								
0.		2.3				13							
0.		1.		1.		1.							
0.	3	0	0	0	2	-1	0	2	1		.0015		
-0.8	1	27	1	82					2	2			
0.		1.2		-1.		1.							
0.	8	7											
0.	1	27	1	82	1								
0.	1	27	1	82	2								

```

0.      2.3      13      1
0.      1.      1.      1.
0 0 0 0 2 -1 0 2 0 0.0015
1 27 1 82
-0.8 1.2 -1. 1.
1 27 1 82 1
1 27 1 82 2
0.      2.3      13      1
0.      1.      1.      1.
3 5 2 -1 2 1 0.0015
1 27 1 82 2 2
-0.2 2.7 -2. 0.9
8 7
1 27 1 82 1
1 27 1 82 2
2 2 1 82 7
2 2 1 82 8
2 2 1 82 9
2 2 1 82 13
2 2 1 82 14
0.      2.3      13      1
0.      1.      1.      1.

```

FLOW OVER A SEMI-INF CYLND (M=4.5)

```

50 125 0 1 0 -1 1 1 1 0 0 15
-25. 0. -25. 1. -24.75 2.5 -24.30 5.
-23.80 7.5 -22.80 10. -21.50 12.5 -20. 15.
-17. 18. -14. 20.7 -11. 22.3 -8. 23.6
-5. 24.2 -2.6 24.6 0. 25.
400 5 5 200 1 800
1. 1. -0.5 -51.5 0. 1. 0.6
0.00128 0. 0. 0.1956E 10
100. 1. 29. 0.
1 1 1 127
0.00128 0. 150000. 1.3210E 10
100. 1.

```

```

0 0 0 0 2 0 0 1 1 0.00010
1 52 1 127 2 2
-100. 0. -100. 0.
8 7
1 52 1 127 1
1 52 1 127 2
0. 1. 1. 1.
3 0 0 2 -1 0 1 0 0.00010
1 52 1 127
-100. 0. -100. 0.
1 52 1 127 1
1 52 1 127 2
0. 5.0 13
0. 1.

```

DETACHED OBLIQUE SHOCK (48 DEG)

```

30 95 0 0 1 0 1 1 1 0 0 2
0. 5.7 -4. 9.7
250 2 4 500 1 500
.10 .20 0. -6.3 0. 1. .75 0.
.001314 0. 0. .19570E+100.
0. 1. 29. 0.
1 1 32 1
.002000 120000. 0. 1.0000E 10
0. 1.

```

```

      0  0  0  0  2  0  0  0  1  .00015
      1 32  1 97  2  1
-0.5  8  7  6.5  -7.  0.
      1 32  1 97  1
      1 32  1 97  2
0.    0  0  1.  0.  0.  1.
      1 32  1 97  2  -1  0  0  0  .00015
-0.5  1  32  1 97  1  0.
      1 32  1 97  2  -7.  0.
1.    1.    4.    13
0.    0.    1.    0.    1.

```

ONE ELECTRODE (BETA=0.)

```

      14  40  0  1  1  0  1  1  2  1  6  0  4  1
8.0   -0.5  8.0  25.  8.0  25.  8.0  71.
100.  1.  100.  1.  00.  17  26
      1  5  5  1  1  1
1.4   1.4  -0.7  -11.  0.  1.  0.75  0.
0.00128 00000.  0.  0.5000E 10+20000.
10.    1.  29.  0.
      1  1  16  42
0.00128 50000.  0.  0.7500E 10+20000.
10.    1.
      3  0  0  0  2  -1  1  0  0  100.
      1 16  1  42
0.    32.  -16.  16.
      1 16  1  42  1
      1 16  1  42  2
-0.15  0.42  33
0.    1.  1.  1.
      0  0  0  0  2  -1  3  0  0  100.
      1 16  1  42
0.    32.  -16.  16.
      1 16  1  42  1
      1 16  1  42  2
-0.15  0.42  33
0.    1.  1.  1.
      0  0  0  0  2  0  1  0  1  .00000005
      1 16  1  42
0.    32.  -16.  16.
      19  20
      1 16  1  42  1
      1 16  1  42  2
0.    1.  1.  1.
      3  0  0  0  2  -1  1  0  0  1250.
      1 16  1  42
0.    32.  -16.  16.
      1 16  1  42  1
      1 16  1  42  2
-0.4   +0.4  32
0.    1.  1.  1.

```

HALL PARAMETER = 5

```

      14  40  0  1  1  1  1  2  1  6  1  4  1
8.0   -0.5  8.  25.  8.  25.  8.  41.
100.  1.  1.  1.  0.  17  26
      1  5  5  1  1  1
1.    1.4  -0.5  -11.  0.  1.  0.10  0.
0.00128 0.  0.  0.5000E 1020000.

```

```

0.      1.      29.      0.
  1      1 16      42
0.00128 50000.  0.      0.7500E 1020000.
0.      1.

      0      0      0      0      2      -1      5
      1      16      1      42
-12.5      37.5      -25.      25.
      1      16      1      42      1
      1      16      1      42      2
-0.2      0.70      33
0.      1.      1.      1.
      0      0      0      0      2      -1      5
      1      16      1      42
-12.5      37.5      -25.      25.
      1      16      1      42      1
      1      16      1      42      2
-10.      80.      32
0.      1.      1.      1.
      3      0      0      0      2      -1
      1      16      1      42
0.      25.      -12.5      12.5
      1      16      1      42      1
      1      16      1      42      2
-0.3      0.3      33
0.      1.      1.      1.
      0      0      0      0      2      -1      5
      1      16      1      42
0.      25.      -12.5      12.5
      1      16      1      42      1
      1      16      1      42      2
-0.1      0.35      33
0.      1.      1.      1.
      0      0      0      0      2      0      0      0      1      1250.
      1      16      1      42
0.      25.      -12.5      12.5
26      27
      1      16      1      42      1
      1      16      1      42      2
0.      1.      1.      1.
      0      0      0      0      2      0      0      0      1      0.00000005
      1      16      1      42
0.      25.      -12.5      12.5
19      20
      1      16      1      42      1
      1      16      1      42      2
0.      1.      1.      1.
      3      0      0      0      2      -1
      1      16      1      42
0.      25.      -12.5      12.5
      1      16      1      42      1
      1      16      1      42      2
-10.      80.      32
0.      1.      1.      1.
      0      0      0      0      2      -1
      1      16      1      42
0.      25.      -12.5      12.5
      1      16      1      42      1
      1      16      1      42      2
-10.      80.      32
0.      1.      1.      1.
FUNCTION BETA(I,J,IHALF,JHALF)
BETA=5.
RETURN
END

```

THREE ELECTRODES (BETA=2.)

14.	30	103	0	1	1	1	1	1	2	1	1	1	4	10
10.			-0.5	14.	75.	25.	14.	50.	00.	24	82	14.		105.
1.0	1	1	10	1	1	1								
0.00128			1.0	-0.5		-16.	0.	1.	0.5000E	1020000.		0.10		0.
0.			1.	29.		0.								
0.00128	1	1	32	105					0.7500E	1020000.				
0.			50000.	0.										
			1.											

	0	0	0	0	2	0	1	0	1	1250.
5.	1	32	1	105						
			60.		-27.5		27.5			
	26	27								
	1	32	1	105	1					
0.	1	32	1	105	2					
			1.		1.		1.			
0.	0	0	0	0	2	-1	0	0	0	100.
5.	1	32	1	105						
			60.		-27.5		27.5			
	1	32	1	105	1					
0.	1	32	1	105	2					
0.			1.0				33			
0.			1.		1.		1.			
	0	0	0	0	2	-1	5	0	0	100.
-20.	1	32	1	105						
			80.		-50.		50.			
	1	32	1	105	1					
0.	1	32	1	105	2					
0#			2.				33			
	3	0	0	0	2	-1	1	0	0	100.
5.	1	32	1	105						
			60.		-27.5		27.5			
	1	32	1	105	1					
0.	1	32	1	105	2					
0.			1.0				33			
0.			1.		1.		1.			

FUNCTION BETA(I,J,IHALF,JHALF)
 BETA=2.
 RETURN
 END

SHOCK INDUCED EDDY CURRENTS

10.5	24	70	0	1	-1	0	-1	1	2	1	0	0	4	1
100.			-0.5	10.5	100.	25.	10.5	25.	00.	17	26	10.5		71.
1.0	30	5	5	30	1	60								
0.00128			1.0	-0.5		-13.	0.	1.	0.5000E	10+20000.		0.75		0.
10.			1.	29.		0.								
0.00128	1	1	26	72										
10.			50000.	0.		0.7500E	10+20000.							
0.0250	1	1	26	1										
10.			50000.	0.		0.7500E	10+20000.							
			1.											

```

0 0 0 0 2 -1 5
1 26 1 72
0. 70. -70. 0.
1 26 1 72 1
1 26 1 72 2
12 12 1 72 13
-0.15 0.42 33
0. 1.
0 0 0 0 2 -1 3 0 0 1250.
1 26 1 72
0. 25. -12.5 12.5
1 26 1 72 1
1 26 1 72 2
-0.15 0.42 33
0. 1. 0.00015 0.00015
0 0 0 0 2 0 1 0 1 1250.
1 26 1 42 1 26 1 72
0. 25. -12.5 12.5
26 27
1 26 1 42 1
1 26 1 42 2
0. 1.
3 0 0 0 2 -1 1 0 0 1250.
1 26 1 42 1 26 1 72
0. 25. -12.5 12.5
1 26 1 42 1
1 26 1 42 2
-0.15 0.42 33
0. 1.
0 0 0 0 2 -1 1 0 0 100.
1 16 1 42
0. 25. -12.5 12.5
1 16 1 42 1
1 16 1 42 2
-0.15 0.42 33
0. 1.
2 0 1 0 2 -1 1 0 0 1250.
1 16 1 72
0. 70. -65. 5.
1 16 1 72 1
1 16 1 72 2
12 12 1 72 9
1.55 3. 13
0. 1.
2 0 1 0 2 -1 1 0 0 1250.
1 16 1 72
0. 70. -65. 5.
1 16 1 72 1
1 16 1 72 2
2 2 1 72 14
-0.15 0.42 33
0. 1.

```

```

SUBROUTINE SPEC
COMMON /V1/ R(52),Z(152),DR(52),DZ(152),U(52,152),V(52,152),E(52,1 A 11
152),RHO(52,152),B(52,152)
COMMON /V4/ IMAX,JMAX,IP1,JP1,IP2,JP2,IAXI,IPTSF,ISYM(4)
REAL*8 R,RIPH,RIMH,RIP3H,RTOP
DO 1 K=1,IP2
DO 1 J=1,JP2
V(K,J)=0.
B(K,J)=20000.
1 CONTINUE

```

```
RETURN
END
FUNCTION BETA(I, J, IHALF, JHALF)
COMMON / V7 / RHO0, VZ, VR, BO, EO, VISCO, PERMO, SIGO, CONDO, CVO, VELOC
1, PHIO
BETA=0.
RETURN
END
FUNCTION GAMM(I, J)
GAMM=1.15
RETURN
END
FUNCTION SIG (I, J, IHALF, JHALF, IN)
COMMON /V14/ NMAGN, NTHRM, NVISC, NCONV, IPDT
SIG=10.##(-10)
NMAGN=99999
RETURN
END
```

C.6 PROGRAM SUGGESTIONS

The most expeditious approach to learning the function of this program and avoiding the numerous pit-falls which discourage further use is to start with one of the many test cases discussed in C.5 and in stages, refine the input to suit the particular needs of the problem in question.

The major and most frequent error that occurs is numerical instability. It is easily detected by observing that velocities and energy grow exponentially in time; the density vanishes or pressures and temperatures become negative. The run will usually terminate abnormally and give various diagnostics. The source of the instability is an excessively large time step. The simple procedure for correcting this error is to reduce the time step through the input parameter STAB ($DT = DT \text{ (Min)} \times \text{STAB}$), which is normally set to 0.75. Reducing STAB by 10 to 50% may in most circumstances result in a stable calculation.

C.7 HULL DIFFERENCE MINORITY REPORT

The development of methodology employed in this program was based strictly on comments prefacing the HULL computer logic. Written by one of the principal authors, Richard E. Durrett, it is entitled "The Hull Difference Minority Report." From this explicit 5-page summary of the HULL technique, a 6500 card FORTRAN IV computer program, the subject of this report, was developed!

MINORITY REPORT ON HULL

THE HULL DIFFERENCE METHOD

THE HULL SYSTEM EMPLOYS THE STANDARD SHELL DIFFERENCE METHOD OR A MORE STABLE, FULLY SECOND ORDER ACCURATE METHOD DEVELOPED BY CAPTAIN MATUSKA AT THE AIR FORCE WEAPONS LABORATORY (AFWL). THESE ARE REFERRED TO AS METHODS 1 AND 2 RESPECTIVELY.

THE SHELL DIFFERENCE METHOD (METHOD 1) IS DETAILED IN AFWL TR 66-141. METHOD 2 IS PRESENTED BELOW.

THE METHOD IS APPLIED TO THE EQUATIONS DESCRIBING THE BEHAVIOR OF A COMPRESSIBLE, NONCONDUCTING, INVISCID FLUID. THE EQUATIONS ARE THOSE DESCRIBING

CONSERVATION OF MASS

$$D(\rho H) + \rho H \text{DIV}(U\#) = 0 \quad (1)$$

CONSERVATION OF MOMENTUM

$$\rho H \text{D}(U\#) + \text{GRAD}(P) = -\rho H \text{G}\# \quad (2)$$

CONSERVATION OF ENERGY

$$\rho H \text{D}(E) + \text{DIV}(P \cdot U\#) = -\rho H \text{U}\# \text{G}\# \quad (3)$$

ALONG WITH THE EQUATION OF STATE

$$P = P(\rho H, I) \quad (4)$$

WHERE

D IS THE LAGRANGIAN DERIVATIVE WITH RESPECT TO TIME

DIV IS THE VECTOR DIVERGENCE

GRAD IS THE GRADIENT VECTOR OPERATOR

ρH = MATERIAL DENSITY (GM/CM**3)

P = PRESSURE (DYNES/CM**2)

I = INTERNAL SPECIFIC ENERGY (ERGS/GM)

J# = FLUID VELOCITY (CM/SEC)

E = I + U#*U#/2 (ERGS/GM)

G# = ACCELERATION DUE TO GRAVITY (CM/SEC**2)

T = TIME (SEC)

AND THE SPECIAL SYMBOL # IS USED TO INDICATE A VECTOR QUANTITY. THE MULTIPLICATION SYMBOL (*) BETWEEN VECTORS INDICATES THE DOT PRODUCT.

EQUATIONS 1 THRU 3 ARE APPROXIMATED BY FINITE DIFFERENCES AND ARE SOLVED EXPLICITLY OVER A DISCRETE TIME INTERVAL DT IN TWO PHASES. THE FIRST PHASE CONSIDERS THE SOLUTION TO EQUATIONS 2 AND 3, WHILE THE SECOND PHASE TREATS EQUATION 1 IN A MANNER WHICH CAUSES DISSIPATION OF KINETIC ENERGY INTO INTERNAL ENERGY, PRINCIPALLY IN THE REGION OF LARGE VELOCITY GRADIENTS. THIS ALLOWS THE CALCULATION OF LARGE DISCONTINUITIES SUCH AS SHOCKS.

THE METHOD WILL BE ILLUSTRATED FOR THE CASE OF TWO-DIMENSIONAL AXISYMMETRIC CYLINDRICAL COORDINATES. EQUATIONS 1 THRU 3 CAN THEN BE WRITTEN AS

$$D(\rho H) + \rho H \text{D}(R \cdot U) + \rho H \text{DZ}(V) = 0 \quad (5)$$

$$\rho H \text{D}(U) + \rho H \text{D}(P) = 0 \quad (6)$$

$$\rho H \text{D}(V) + \rho H \text{D}(P) = -\rho H \text{G} \quad (7)$$

$$\rho H \text{D}(E) + \rho H \text{D}(R \cdot P \cdot U) + \rho H \text{D}(P \cdot V) = -\rho H \text{U} \cdot \text{G} \quad (8)$$

WHERE

R = RADIAL COORDINATE

Z = AXIAL COORDINATE

PDR = PARTIAL DERIVATIVE WITH RESPECT TO THE RADIAL COORDINATE

PDZ = PARTIAL DERIVATIVE WITH RESPECT TO THE AXIAL COORDINATE

J = COMPONENT OF U# IN THE RADIAL DIRECTION

V = COMPONENT OF U# IN THE AXIAL DIRECTION.

IN ESTABLISHING FINITE DIFFERENCE ANALOGS TO EQUATIONS 5 THRU 8 WE CONSIDER A DISCRETE SUBSET OF F(R,Z,T) BY DEFINING

$$F(I, J, N) = F(R(I), Z(J), T(N))$$

WHERE R(I), Z(J), AND T(N) ARE PARTICULAR VALUES OF R, Z, AND T RESPECTIVELY, AND THE I, J, AND N ASSUME INTEGER VALUES IN THE RANGE 1 TO IMAX FOR I, 1 TO JMAX FOR J, AND 0 TO NMAX FOR N. THE R(I) AND Z(J) ARE DEFINED IN TERMS OF A GIVEN SET OF DR(I) AND DZ(J) SUCH THAT

$$R(I) = R(0) + (\text{SUM}, K=1, I-1, (DR(K))) + DR(I)/2 \quad \text{FOR } I=2, \dots, \text{IMAX}$$

$$R(1) = R(0) + DR(1)/2$$

$$Z(J) = Z(0) + (\text{SUM}, K=1, J-1, (DZ(K))) + DZ(J)/2 \quad \text{FOR } J=2, \dots, \text{JMAX}$$

$$Z(1) = Z(0) + DZ(1)/2$$

WHERE P(0) AND Z(0) HAVE SOME SPECIFIED VALUES.

THE HYDRODYNAMIC VARIABLES ρH , U, V, AND I (INTERNAL SPECIFIC ENERGY) ARE DEFINED FOR EACH SET OF COORDINATES (I, J) AT A PARTICULAR TIME T(N). THE PRESSURE P(I, J, N) IS DEFINED AT EACH POINT BY THE EQUATION OF STATE (EQUATION 4).

INTERPOLATED VALUES OF THE HYDRODYNAMIC VARIABLES OF THE FORM F(I+1/2, J, N), F(I, J+1/2, N), OR F(I, J, N+1/2), OR SIMILAR FORMS, ARE DEFINED IN TERMS OF THE F(I, J, N). IN GENERAL

$$F(I+1/2, J, N) = (F(I+1, J, N) + F(I, J, N))/2$$

AND

$$F(I, J+1/2, N) = (F(I, J+1, N) + F(I, J, N))/2$$

THIS DEFINITION WILL APPLY EXCEPT WHERE EXPLICITLY NOTED.

PHASE I

IN METHOD 2 THE FINITE DIFFERENCE ANALOGS TO EQUATIONS 6 THRU 8 ARE CHOSEN AS

$$U(I, J, N+1) = U(I, J, N) - DT * (P(I+1/2, J, N+1/2) - P(I-1/2, J, N+1/2)) / (\rho H(I, J, N) * DR(I)) \quad (9)$$

$$V(I, J, N+1) = V(I, J, N) - DT * (P(I, J+1/2, N+1/2) - P(I, J-1/2, N+1/2)) / (\rho H(I, J, N) * DZ(J) - DT * G(J)) \quad (10)$$

$$E(I, J, N+1) = E(I, J, N) - DT * (\rho H(I, J, N) * ((R(I+1/2) * P(I+1/2, J, N+1/2) * U(I+1/2, J, N+1/2) - R(I-1/2) * P(I-1/2, J, N+1/2) * U(I-1/2, J, N+1/2)) / (R(I) * DR(I)) + (P(I, J+1/2, N+1/2) - P(I, J-1/2, N+1/2)) / DZ(J) - DT * G(J))$$

Figure C.31 Synopsis of HULL Code

$$\frac{V(I, J+1/2, N+1/2) - P(I, J-1/2, N+1/2) * V(I, J-1/2, N+1/2)}{DZ(J)} - DT * V(I, J, N+1) * G(J) \quad (11)$$

WHERE

$$\begin{aligned} DT &= T(N+1) - T(N) \\ R(I+1/2) &= R(I) + DR(I)/2 \\ R(I-1/2) &= R((I-1) + 1/2) \\ Z(J+1/2) &= Z(J) + DZ(J)/2 \\ Z(J-1/2) &= Z((J-1) + 1/2) \\ G(J) &= \text{VALUE OF G AT Z(J)}. \end{aligned}$$

ALL THE VALUES APPEARING IN EQUATIONS 9 THRU 11 ARE IMMEDIATELY KNOWN EXCEPT THE TIME ADVANCED (N+1/2) VALUES FOR PRESSURE AND VELOCITY. THESE TIME ADVANCED VALUES ARE USED SO THAT THE APPROXIMATIONS TO THE PARTIAL DERIVATIVES APPEARING IN EQUATIONS 6 THRU 8 MAY BE CENTERED IN TIME AND SPACE. IN THE CASE WHERE

$$\begin{aligned} DP(I) &= \text{CONSTANT} \quad \text{FOR } I=1, \dots, \text{IMAX} \\ \text{AND} \\ DZ(J) &= \text{CONSTANT} \quad \text{FOR } J=1, \dots, \text{JMAX} \end{aligned}$$

THIS PRODUCES A FULLY SECOND ORDER ACCURATE DIFFERENCE METHOD. IN A REGION WHERE THE DR(I) AND DZ(J) ARE NOT CONSTANT THE SECOND ORDER ACCURACY IS LOST. THIS ADVERSELY AFFECTS THE STABILITY OF THE FIRST PHASE CALCULATION. THE AMOUNT OF INSTABILITY WHICH MAY BE OBTAINED IS RELATED TO THE MAGNITUDE OF THE INCREMENTAL CHANGES IN DR(I) AND DZ(J).

MOST OF THE COMPUTATIONS IN THE FIRST PHASE ARE EXPENDED IN OBTAINING THE TIME ADVANCED VALUES FOR PRESSURE AND VELOCITY. THE TIME ADVANCED VELOCITIES ARE OBTAINED BY DIFFERENCING EQUATIONS 6 AND 7 AS

$$\begin{aligned} J(I+1/2, J, N+1/2) &= U(I+1/2, J, N) - DT / (2 * RHO(I+1/2, J, N+1/2)) \\ &\quad * ((P(I+1, J, N) - P(I, J, N)) / (R(I+1) - R(I))) \\ &\quad (12) \\ V(I, J+1/2, N+1/2) &= V(I, J+1/2, N) - DT / (2 * RHO(I, J+1/2, N+1/2)) \\ &\quad * ((P(I, J+1, N) - P(I, J, N)) / (Z(J+1) - Z(J))) \\ &\quad - G(I+1/2) * DT / 2 \quad (13) \end{aligned}$$

WHERE

$$G(J+1/2) = (G(J) + G(J+1)) / 2.$$

THE TIME ADVANCED DENSITIES APPEARING IN EQUATIONS 12 AND 13 ARE OBTAINED BY DIFFERENCING EQUATION 5 AS

$$\begin{aligned} RHO(I+1/2, J, N+1/2) &= RHO(I+1/2, J, N) * (1 - DT / (2 * R(I+1/2))) * (R(I+1) \\ &\quad * U(I+1, J, N) - R(I) * U(I, J, N)) / (R(I+1) - R(I)) \quad (14) \\ RHO(I, J+1/2, N+1/2) &= RHO(I, J+1/2, N) * (1 - DT / 2 * (V(I, J+1, N) - V(I, J, N)) \\ &\quad / (Z(J+1) - Z(J))) \quad (15) \end{aligned}$$

WHERE

$$\begin{aligned} RHO(I+1/2, J, N) &= (M(I, J, N) + M(I+1, J, N)) / (PI * (R(I+1/2))^2 \\ &\quad - R(I-1/2) * 2 * DZ(J)) \\ RHO(I, J+1/2, N) &= (M(I, J, N) + M(I, J+1, N)) / (PI * (R(I+1/2))^2 \\ &\quad - R(I-1/2) * 2 * (DZ(J) + DZ(J+1))) \end{aligned}$$

AND THE MASS ASSOCIATED WITH A POINT (I, J, N) IS DEFINED BY

$$M(I, J, N) = RHO(I, J, N) * (PI * (R(I+1/2))^2 - R(I-1/2) * 2 * DZ(J))$$

WHERE PI=3.14159... AND R(I+3/2)=R((I+1)+1/2).

THE TIME ADVANCED PRESSURE APPEARING IN EQUATIONS 9 THRU 11 REQUIRES A LITTLE MORE EFFORT. FIRST AN ALTERNATIVE ENERGY EQUATION CAN BE OBTAINED FROM EQUATIONS 2 AND 3 AS

$$\begin{aligned} RHO * D(I) + P * DIV(U\#) &= 0. \quad (16) \\ \text{AN EFFECTIVE GAMMA CAN BE DEFINED BY} \\ GAMMA &= 1 + P / (RHO * I). \quad (17) \end{aligned}$$

WE WILL ASSUME FOR THE PURPOSES OF CALCULATING A HALF TIME STEP ADVANCED PRESSURE, WHICH IN TURN IS USED IN APPROXIMATING THE PARTIAL DERIVATIVES IN EQUATIONS 9 THRU 11, THAT THE LAGRANGIAN DERIVATIVE WITH RESPECT TO TIME OF GAMMA IS SMALL AND CAN BE IGNORED. IN APPLICATION IT IS ONLY REQUIRED THAT THE CHANGE IN GAMMA AT A PARTICULAR POINT BE SMALL OVER A TIME OF DT/2.

TAKING THE LAGRANGIAN DERIVATIVE WITH RESPECT TO TIME IN EQUATION 17 AND USING EQUATIONS 1 AND 16 WE CAN WRITE

$$D(P) + GAMMA * P * DIV(U\#) = 0. \quad (18)$$

EQUATION 18 IS USED TO OBTAIN TIME ADVANCED PRESSURES GIVEN BY

$$\begin{aligned} P(I+1/2, J, N+1/2) &= P(I+1/2, J, N) * (1 - DT * GAMMA(I+1/2, J, N)) * (R(I+1) \\ &\quad * U(I+1, J, N) - R(I) * U(I, J, N)) / (2 * (R(I+1/2) * R(I+1) \\ &\quad - R(I))) \\ P(I, J+1/2, N+1/2) &= P(I, J+1/2, N) * (1 - DT * GAMMA(I, J+1/2, N)) \\ &\quad * (V(I, J+1, N) - V(I, J, N)) / (2 * (Z(J+1) - Z(J))) \end{aligned}$$

WHERE GAMMA IS OBTAINED FROM EQUATION 17 AS

$$\begin{aligned} GAMMA(I+1/2, J, N) &= 1 + P(I+1/2, J, N) / (RHO(I+1/2, J, N) * I(I+1/2, J, N)) \\ GAMMA(I, J+1/2, N) &= 1 + P(I, J+1/2, N) / (RHO(I, J+1/2, N) * I(I, J+1/2, N)). \end{aligned}$$

ALL QUANTITIES NEEDED TO SOLVE EQUATIONS 9, 10, AND 11 ARE NOW DEFINED. SOLUTION OF THESE EQUATIONS WILL COMPLETE A SECOND ORDER ACCURATE LAGRANGIAN CALCULATION. THE NEXT STEP WOULD NORMALLY BE THAT OF TRANSPORTING MESH VERTICES. INSTEAD WE CHOOSE TO FLUX THE HYDRODYNAMIC QUANTITIES TO RETAIN THE ORIGINAL MESH CONFIGURATION. THIS CALCULATION IS DONE IN PHASE II.

PHASE II

CHANGES IN DENSITY ARE COMPUTED IN PHASE II BY CALCULATING A MASS FLUX BETWEEN MESH POINTS AND THEN TRANSPORTING THE APPROPRIATE AMOUNT OF MASS FROM POINT TO POINT. THE TRANSPORTED MASS CARRIES WITH IT A PROPORTIONATE AMOUNT OF INTERNAL ENERGY AND MOMENTUM. THE VELOCITIES AND SPECIFIC INTERNAL ENERGY ARE THEN REDEFINED AT EACH MESH POINT BY CONSERVING MOMENTUM AND TOTAL ENERGY AT THAT POINT.

THE MASS FLUX BETWEEN MESH POINTS IS DEFINED AS THE PRODUCT OF THE INTERPOLATE VELOCITY, THE DENSITY AS DEFINED IN EQUATION 8, SOLUTION OF EQUATION 1, THE INTERMEDIATE CROSS SECTIONAL AREA, AND THE TIME STEP. THE EQUATIONS ARE

$$\begin{aligned} MF(I+1/2, J, N+1) &= U(I+1/2, J, N+1) * RHO(I+1/2, J, N+1) * 2 * PI * R(I+1/2) \\ &\quad * DZ(J) * DT \\ MF(I, J+1/2, N+1) &= V(I, J+1/2, N+1) * RHO(I, J+1/2, N+1) * 2 * PI * R(I) * DR(I) \\ &\quad * DT \end{aligned}$$

WHERE THE TIME ADVANCED DENSITIES ARE OBTAINED BY DIFFERENCING EQUATION 5 AS

$$\begin{aligned} RHO(I+1/2, J, N+1) &= RHO(I+1/2, J, N) * (1 - DT / R(I+1/2)) * (R(I+1) \\ &\quad * U(I+1, J, N+1) - R(I) * U(I, J, N+1)) / (R(I+1) - R(I)) \\ RHO(I, J+1/2, N+1) &= RHO(I, J+1/2, N) * (1 - DT * (V(I, J+1, N+1) - V(I, J, N+1)) \\ &\quad / (Z(J+1) - Z(J))) \end{aligned}$$

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Figure C.31 Continued

```

WHERE
-----
ID=I   IF U(I+1/2,J,N+1) GT 0
  =I+1 IF U(I+1/2,J,N+1) LT 0
-----
JD=J   IF V(I,J+1/2,N+1) GT 0
  =J+1 IF V(I,J+1/2,N+1) LT 0.
-----
THIS IS THE CLASSICAL DONOR CELL DIFFERENCING TECHNIQUE. THE MOST
OBVIOUS ADVANTAGES OF THIS TECHNIQUE ARE ITS RIGID NUMERICAL
CONSERVATION AND ITS STABILITY. THIS SCHEME ALSO INSURES THAT MORE
MATERIAL CAN NOT BE REMOVED FROM A POINT THAN IS PRESENT.
-----
HULL HAS A CONTINUOUS REZONE CAPABILITY. WHEN THIS IS EMPLOYED
THE INTERPOLATED VELOCITIES APPEARING IN THE MASS FLUX EQUATIONS ARE
REPLACED BY
-----
U(I+1/2,J,N+1)-UR(I+1/2,J,N+1)
V(I,J+1/2,N+1)-VR(I,J+1/2,N+1)
-----
WHERE UR AND VR ARE THE INTERPOLATED GRID VELOCITIES (DETERMINED
ARBITRARILY BY HOW FAST ONE WISHES TO TRANSPORT THE COORDINATE GRID).
THE CORRESPONDING MOMENTUM FLUXES ARE
-----
UF(I+1/2,J,N+1)=MF(I+1/2,J,N+1)*U(ID,J,N+1)
VF(I+1/2,J,N+1)=MF(I+1/2,J,N+1)*V(ID,J,N+1)
-----
UF(I,J+1/2,N+1)=MF(I,J+1/2,N+1)*U(I,JD,N+1)
VF(I,J+1/2,N+1)=MF(I,J+1/2,N+1)*V(I,JD,N+1)
-----
AND THE ENERGY FLUXES ARE
-----
EF(I+1/2,J,N+1)=MF(I+1/2,J,N+1)*E(ID,J,N+1)
EF(I,J+1/2,N+1)=MF(I,J+1/2,N+1)*E(I,JD,N+1).
-----
WHEN THESE QUANTITIES ARE FLUXED FINAL VALUES FOR MASS, DENSITY,
VELOCITY, AND ENERGY ARE COMPUTED BY
-----
M(I,J)=M(I,J,N)+MF(I-1/2,J,N+1)+MF(I,J-1/2,N+1)
      -MF(I+1/2,J,N+1)-MF(I,J+1/2,N+1)
-----
RHO(I,J)=M(I,J)/(PI*(R(I+1/2)**2-R(I-1/2)**2)*DZ(J))
-----
U(I,J)=(U(I,J,N+1)*M(I,J,N)+UF(I-1/2,J,N+1)+UF(I,J-1/2,N+1)
      -UF(I+1/2,J,N+1)-UF(I,J+1/2,N+1))/M(I,J)
-----
V(I,J)=(V(I,J,N+1)*M(I,J,N)+VF(I-1/2,J,N+1)+VF(I,J-1/2,N+1)
      -VF(I,J+1/2,N+1)-VF(I+1/2,J,N+1))/M(I,J)
-----
Y(I,J)=(E(I,J,N+1)*M(I,J,N)+EF(I-1/2,J,N+1)+EF(I,J-1/2,N+1)
      -EF(I+1/2,J,N+1)-EF(I,J+1/2,N+1)-(U(I,J)**2+V(I,J)**2)
      *M(I,J)/2)/M(I,J)
-----
E(I,J)=I(I,J)+(U(I,J)**2+V(I,J)**2)/2
-----
WHERE THE LACK OF A TIME SPECIFICATION INDICATES FINAL VALUES FOR THIS
TIME STEP.

```

Figure C.31 Continued

```

C  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 1
C  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX IBM 370 VERSION XXXXXXXXXXXXXXXXXXXXXXXX 2
C  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX CALCOMP PLOTTER XXXXXXXXXXXXXXXXXXXXXXXX 3
C  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 4
C  ----- 5
C  I I 6
C  I I 7
C  I I 8
C  I I 9
C  I I 10
C  I I 11
C  I I 12
C  I I 13
C  I I 14
C  I I 15
C  I I 16
C  I I 17
C  I I 18
C  I I 19
C  I I 20
C  ----- 21
C  22
C  23
C  24
C  25
C  26
C  27
C  28
C  29
C  30
C  31
C  32
C  33
C  34
C  35
C  36
C  37
C  38
C  39
C  40
C  41
C  42
C  43
C  44
C  45
C  46
C  47
C  48
C  49
C  50
C  51
C  52
C  53
C  54
C  55
C  56
C  57
C  58
C  59
C  60
C  61
C  62
C  63

```

A NUMERICAL PROCEDURE FOR PREDICTING TRANSIENT SHOCK, BOUNDARY LAYER AND MAGNETOHYDRODYNAMIC PHENOMENA
BY LAURENCE ALAN FELDMAN
FEB 1975-JUNE 1978
AUBURN UNIVERSITY, AUBURN, AL.
UNIV OF TENN SPACE INSTITUTE, TULLAHOOMA, TENN.
ARNOLD AFS (AEDC), TENN.
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LABELLED COMMON BLOCK "CARRY" CONTROLS THE GRID RESOLUTION AND THUS, THE SIZE OF CENTRAL MEMORY. IF THE PROGRAM IS TOO LARGE, REDUCE THE DIMENSIONS (RESTRICTING THE GRID SIZE) OF THE VARIABLE ARRAYS LISTED IN "CARRY".

ON THE IBM 360 OR 370 MODELS, DOUBLE PRECISION MUST BE USED FOR THE FOLLOWING VARIABLES: R,RIPH,RIMH,RIP3H AND RD. SIMPLY INSERT INTO ALL SUBROUTINES THAT EMPLOY LABELLED COMMON BLOCK "CARRY" THE FOLLOWING STATEMENT (BEGINNING IN COLUMN 7) REAL*8 R,RIPH,RIMH,RIP3H,RD THIS CARD COMES AFTER THE LAST COMMON OR DIMENSION STATEMENT.

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
XXXXXXXXXXXXXXXXXXXXXXXXXXXXX MAIN PROGRAM XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

GRID SET UP FOR A MAXIMUM OF 45 X 225 CELLS. INCREASING THE RESOLUTION BEYOND THESE VALUES WILL REQUIRE AN INCREASE IN THE APPROPRIATE ARRAYS.

```

COMMON /CMESH/ KMAX, JMAX, KP1, JP1, KP2, JP2
COMMON /COUTP/ TITLE(15), KPDEL, JPDEL, NPLDT, NPRN, NDIGPL, NGRAPH
COMMON /CGRID/ R(45), RD(45), Z(225), DR(45), DZ(225), XD(45), ZMIN, RMIN, D1Z0, DRO, IGRAPH(225), NBOUND
COMMON /CBOUND/ DANGLE(225), IOBK(225), IOBL(225), ISYM(4), IAXI, IOBQ
COMMON /CMHD/ INSK(225), DVOLT, BASEP, DPDT, SPACE, SPINSL, JPLMIN, JPLMAX
COMMON /CINIT/ RHDO, VZ, VR, BO, BRO, BZO, EO, PHIO, PERMO, VELDC, ARFV, PERM1, NVECT, NPDIM
COMMON /CCALC/ BL, EMF, MCALC, NMAGN, NTHRM, IPDT, IDFN, IPTSF
COMMON /TPLY/ TPLTMI, TPLTMA, TPLTDE, TPLTDL, TZERO, T

```

	REAL*8 R,RD	64
C		65
C		66
C	FOR IBM 370, REPLACE WITH "CALL DRIVER"	67
	CALL DRIVER	68
	CALL SECONO (A)	69
	WRITE (6,10) A	70
	CALL PLOTTE	71
	CALL SECONO (A)	72
	WRITE (6,10) A	73
	CALL EXIT	74
C		75
C		76
C		77
	10 FORMAT (12H CP SECONDS,2X,E12.4)	78
	END	79
	SUBROUTINE DRIVER	80
C		81
C		82
C	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX	83
C	EXECUTIVE ROUTINE CALLING HYDRO: PHASE I AND II, THERMAL CONDUCT-	84
C	ION, MAGNETIC INDUCTION, TIME-STEP, INPUT/OUTPUT AND GRAPH	85
C	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX	86
C		87
C		88
	COMMON /CARRAY/ RHO(45,225),U(45,225),V(45,225),E(45,225),PHI(45,	89
	1225),BO(1,1),BR(1,1),BZ(1,1),DE(1,1)	90
	COMMON /COUTP/ TITLE(15),KPDEL,JPDEL,NPLOT,NPRN,NDIGPL,NGRAPH	91
	COMMON /CMESH/ KMAX,JMAX,KP1,JP1,KP2,JP2	92
	COMMON /CBOUND/ DANGLE(225),IOBK(225),IOBL(225),ISYM(4),IAXI,IOBO	93
	COMMON /GRAVTY/ GC,GR,GZ	94
	COMMON /CTIME/ TIME,DT,DTT,STAB,MINDT,MAXDT,NCYCLE,NMAX	95
	COMMON /CGRID/R(45),RD(45),Z(225),DR(45),DZ(225),XD(45),ZMIN,RMIN,D	96
	1ZO,DRO,IGRAPH(225),NBOUND	97
	COMMON /CCALC/ BL,EMF,MCALC,NMAGN,NTHRM,IPOT,IDFN,IPTSF	98
	COMMON /CINIT/ RHO0,VZ,VR,BO,BRO,BZO,EO,PHIO,PERMO,VELOC,ARFV,PERM	99
	1,NVECT,NPDIM	100
	COMMON/CMHD/INSJ(225),DVOLT,BASEP,DPOT,SPACE,SPINSL,JPLMIN,JPLMAX	101
	COMMON/CMATRX/ ACDEF(225),BCDEF(225),CCDEF(225),DCDEF(225),SUB(225	102
	1),DIAG(225),SUP(225),CONST(225)	103
	COMMON/CSTORE/RHOF(2,225),UF(2,225),VF(2,225),EF(2,225),MFA(225),	104
	1UA(225),VA(225),UFA(225),VFA(225),EFA(225),PA(225)	105
	COMMON/CSTRSS/TRRA(225),TZZA(225),TODA(225),TRZA(225),VISC,VISCO	106
	COMMON /CMAGN/BFA(225),BZZA(225),BZFA(225),BF(2,225),BFR(2,225),	107
	1BFZ(2,225)	108
	COMMON/ETRODE/ANODE(225),CATHOD(225)	109
	REAL*8 R,RD	110
C		111
C		112
	KL=0	113
	NFLD=0	114
	NCOND=0	115
	NVISC=1000	116
	IDFN=0	117
	READ (5,90) (TITLE(I),I=1,15),IPRN	118
	WRITE (6,100) (TITLE(I),I=1,15)	119
	IF (IPRN.EQ.9) GO TO 80	120
	NCYCLE=0	121
	DT=10, **(-12)	122
	IPR=1	123
	GZ=0.	124
	GR=0.	125
C	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX	126
C	CALLING FOR INPUT AND SETTING INITIAL AND BOUNDARY CONDITIONS	127

C	*****	128
	CALL INPUT	129
	NPOT=IPOT	130
	IPRNT=IPRN	131
10	CALL BOUND	132
	CNPRNT=NPRN	133
	CNPRNT=CNPRNT/10.	134
	IF (CNPRNT.GT.1) IPR=CNPRNT	135
	IF (NPOT.LT.IPOT.OR.IPOT.EQ.0) GO TO 30	136
C	*****	137
C	***** INITIAL CONVERGENCE OF CURRENT STREAM FUNCTION *****	138
C	***** OR POTENTIAL *****	139
C	*****	140
	IDFN=1	141
	CALL BOUND	142
	KLMAX=DPOT	143
	IF (NCYCLE.EQ.0) KLMAX=BASEP	144
	DO 20 KJ=1,KLMAX	145
	KL=KL+1	146
	WRITE (6,110) KL	147
	CALL EFIELD	148
20	CONTINUE	149
30	CONTINUE	150
C	*****	151
C	***** OUTPUT AND PLOT DATA *****	152
C	*****	153
	IF (MOD(NCYCLE,IPR).EQ.0) WRITE (6,150) TIME,DT,NCYCLE	154
	IF (MOD(NCYCLE,NPRN).EQ.0.) CALL OUTPUT	155
	IF (MOD(NCYCLE,NPLOT).EQ.0.AND.NPDIM.GT.0) CALL GRAPH	156
	IF (NCYCLE.GT.NMAX) GO TO 70	157
C	*****	158
C	***** PHASE I (HYDRO) *****	159
C	*****	160
	CALL HULLP1	161
C	*****	162
C	***** COMPUTING TIME STEP AND BOUNDARY CONDITIONS *****	163
C	*****	164
	CALL TMESTP	165
	CALL BOUND	166
	IF (NCOND.LT.NTHRM) GO TO 50	167
C	*****	168
C	***** THERMAL CONDUCTION *****	169
C	*****	170
	NCOND=0	171
	IDFN=2	172
	CALL BOUND	173
	WRITE (6,120)	174
	CALL TEMDIF	175
	DO 40 K=2,KP1	176
	DO 40 J=2,JP1	177
	ENERGY=E(K,J)-0.5*(U(K,J)**2+V(K,J)**2)	178
	E(K,J)=CV(K,J,0,0)*DE(K,J)-ENERGY+0.5*(U(K,J)**2+V(K,J)**2)	179
40	CONTINUE	180
50	CONTINUE	181
C	*****	182
C	***** MAGNETIC INDUCTION *****	183
C	*****	184
	IF (NFLD.LT.NMAGN) GO TO 60	185
	NFLD=0	186
	IDFN=1	187
	CALL BOUND	188
	WRITE (6,130)	189
	CALL DFSN	190
60	CONTINUE	191

C	UNITS	256
C	RHO GM CM-3 K GM CM SEC-3 K-1 B GAUSS	257
C		258
C	U CM SEC-1 CV ERG GM-1 K-1	259
C		260
C	R CM T DYNE-CM	261
C		262
C	VISC GM CM-1 SEC-1 (PS)	263
C		264
C	B = GAUSS (GM/ABCDUL /SEC) = 10-4 WEBER/METER2	265
C		266
C	PERM = 4*PI (GM-CM/ABCDUL2) = 4*PI*10-7 WEBER/AMP/METER	267
C		268
C	COND = (SEC-ABCDUL2/GM/CM3 = 10-11 1/OHM/METER	269
C		270
C	IRST=(0) NO RESTART, =(-1) WRITE RESTART TAPE, =(1) READ RESTART	271
C		272
C	I=INVISCID(BL=0.); L=LAMINAR(BL=1.); T=TURBULENCE(BL=2.)	273
C	NO EMF(EMF=0.); M=MAGN INDC(EMF=1.); P=LORENTZ(EMF=2.)	274
C	MCALC 0 1 2 3 4 5 6 7 8	275
C	I L T I,M L,M T,M I,P L,P T,P	276
C		277
C		278
C		279
	BL=0.	280
	SPINSL=0.	281
	SPACE=0.	282
	EMF=0.	283
	PI=3.1416	284
	WRITE (6,310)	285
C		286
C	INITIALIZING CELL VALUES AND DEFINING MATERIAL	287
C	PROPERTIES	288
C		289
	READ (5,160) KMAX, JMAX, IAXI, IPTSF, ISYM(1), ISYM(2), ISYM(3), ISYM(4),	290
	INVECT, NPDIM, MCALC, IRST, IOBQ, IPOT	291
	IF (MCALC.EQ.1.OR.MCALC.EQ.4.OR.MCALC.EQ.7) BL=1.	292
	IF (MCALC.EQ.2.OR.MCALC.EQ.5.OR.MCALC.EQ.8) BL=2.	293
	IF (MCALC.GT.2.AND.MCALC.LT.6) EMF=1.	294
	IF (MCALC.GT.5) EMF=2.	295
	IBL=1.+BL*3.	296
	IBH=IBL+2	297
	IEMFL=1.+EMF*3.	298
	IEMFH=IEMFL+2	299
	WRITE (6,140) (BLAYER(I), I=IBL, IBH), (ELECT(J), J=IEMFL, IEMFH)	300
	IF (IOBQ.EQ.0) GO TO 30	301
	DO 10 N=1,25	302
	RD(N)=0.	303
	10 XD(N)=0.	304
	IDK=IABS(IOBQ)	305
	READ (5,170) (RD(I), XD(I), I=1, IDK)	306
C	IF (NVECT.EQ.2) READ (5,120) (RB(I), XB(I), I=1, IDK)	307
	20 IF (IPOT.EQ.0) GO TO 30	308
	READ (5,180) SPACE, SPINSL, BASEP, DPOT, DVOLT, JPLMIN, JPLMAX	309
	30 READ (5,190) NPRN, KPDEL, JPDEL, NPLOT, NOIGPL, NMAX, NCYCLE	310
	READ (5,200) DZO, DRO, ZMIN, RMIN, MINDT, MAXDT, STAB, TZERO	311
	READ (5,210) RHOQ, VZ, VR, EQ, BO, BRO, BZO, PHIO	312
	READ (5,220) VISCO, PERMO, MW, ARFV	313
	TIME=TZERO	314
	PERMO=PERMO*4.*PI	315
	KP1=KMAX+1	316
	JP1=JMAX+1	317
	KP2=KMAX+2	318
	JP2=JMAX+2	319

	WRITE (6,240) KMAX, JMAX, IAXI, IPTSF, ISYM(1), ISYM(2), ISYM(3), ISYM(4)	320
	1, NVECT, NPDIM, MCALC, IRST, IOBQ, IPDT	321
	IF (IOBQ.NE.0) WRITE (6,245) (RD(I), XD(I), I=1, IOK)	322
	IF (IOBQ.NE.0) WRITE (6,120)	323
	IF (IPDT.NE.0) WRITE (6,250) SPACE, SPINSL, BASEP, DPDT, DVOLT, JPLMIN,	324
	1 JPLMAX	325
	WRITE (6,260) NPRN, KPDEL, JPDEL, NPLDT, NDIGPL, NMAX, NCYCLE	326
	WRITE (6,270) DZO, DRO, ZMIN, RMIN, MINDT, MAXDT, STAB, TZERO	327
	WRITE (6,280) RHDQ, VZ, VR, EO, BO, BRO, BZO, PHIO	328
	WRITE (6,290) VISCO, PERMO, MW, ARFV	329
	DO 40 J=1, JP2	330
	IOBL(J)=KP2+1	331
	IOBK(J)=KP2+1	332
	IGRAPH(J)=KP2+1	333
	DANGLE(J)=0.	334
	INSJ(J)=0	335
	DO 40 K=1, KP2	336
	RHD(K, J)=RHDQ	337
	U(K, J)=VZ	338
	V(K, J)=VR	339
	E(K, J)=EO	340
	IF (EMF.EQ.2.) PHI(K, J)=PHIO	341
	IF (EMF.NE.1.) GO TO 40	342
	BO(K, J)=BO	343
	BR(K, J)=BRO	344
	BZ(K, J)=BZO	345
	40 CONTINUE	346
	PERM=PERMO	347
	VISC=VISCO	348
C	*****	349
C	***** ASSIGNING VALUES TO SPECIAL CELLS *****	350
C	*****	351
	50 READ (5,230) K1, J1, K2, J2, BRHDO, BVZ, BVR, BEO, BBO, BBRO, BBZO, BPHIO, BVI	352
	ISCO, BPERMO	353
	IF (K1.EQ.0) GO TO 80	354
	BPERMO=BPERMO*4.*PI	355
	WRITE (6,300) K1, J1, K2, J2, BRHDO, BVZ, BVR, BEO, BBO, BBRO, BBZO, BPHIO, BV	356
	ISCO, BPERMO	357
	DO 70 K=K1, K2	358
	DO 70 J=J1, J2	359
	RHD(K, J)=BRHDO	360
	V(K, J)=BVR	361
	U(K, J)=BVZ	362
	E(K, J)=BEO	363
	IF (EMF.NE.1.) GO TO 60	364
	BO(K, J)=BBO	365
	BR(K, J)=BBRO	366
	BZ(K, J)=BBZO	367
	60 CONTINUE	368
	IF (EMF.EQ.2.) PHI(K, J)=BPHIO	369
	VISC=BVISCO	370
	PERM=BPERMO	371
	70 CONTINUE	372
	GO TO 50	373
	80 CONTINUE	374
	WRITE (6,310)	375
	WRITE (6,130)	376
	IF (IRST.LT.1) GO TO 110	377
C	*****	378
C	***** READ INPUT TAPE FOR RESTART *****	379
C	*****	380
	REWIND 15	381
	READ (15) IRST, NCYCLE, T, DT	382
	NMAX=NCYCLE+NMAX	383

```

TIME=T 384
WRITE (6,150) IRST,NCYCLE,TIME 385
DO 100 IZ=1,JP2 386
DO 100 IX=1,KP2 387
IF (EMF.NE.1.) GO TO 90 388
BFT=BQ(IX,IZ) 389
BFR=BR(IX,IZ) 390
BFZ=BZ(IX,IZ) 391
90 CONTINUE 392
IF(EMF.EQ.2.) BPHI=PHI(IX,IZ) 393
READ(15) RHD(IX,IZ),U(IX,IZ),V(IX,IZ),E(IX,IZ),BFT,BFR,BFZ,BPHI 394
100 CONTINUE 395
110 CONTINUE 396
CALL GEOM 397
RETURN 398
C 399
C 400
C 401
120 FORMAT (//) 402
130 FORMAT(1H1) 403
140 FORMAT (//,20X,3A4,5X,3A4,/) 404
150 FORMAT (1X,120(1HX),/,25X,14HRESTART TAPE ,13,2X,10HFDR CYCLE ,15 405
1,2X,8HAT TIME ,E12.4,4H SEC./,1X,120(1HX)) 406
160 FORMAT (16I5) 407
170 FORMAT (8E10.4) 408
180 FORMAT (5E10.4,2I5) 409
190 FORMAT (8I5) 410
200 FDRMAT (8E10.4) 411
210 FDRMAT (8E10.4) 412
220 FDRMAT (8E10.4) 413
230 FDRMAT (4I5,/,8E10.4,/,8E10.4) 414
240 FDRMAT (9H KMAX ,9H JMAX ,9H IAXI ,9H IPTSF ,9H ISYM(1) 415
1 ,9H ISYM(2) ,9H ISYM(3) ,9H ISYM(4) ,9H NVECT ,9H NPDIM ,9H 416
2M CALC ,9H IRST ,9H IOBO ,9H IPDT ,/,14(3X,I3,3X),/) 417
245 FDRMAT(2X,4(11H RD ,11H XD ),/,2X,8(1X,F10.2),/) 418
250 FDRMAT (2X,10H SPACE ,2X,10H SPINSL ,2X,10H BASEP ,2X,10H 419
1 DPDT ,2X,10H DVOLT ,2X,6HJPLMIN,2X,6HJPLMAX,/,5(2X,E10.4),2 420
2(2X,I6),/) 421
260 FDRMAT (10H NPRN ,10H KPDEL ,10H JPDEL ,10H NPLDT ,10 422
1H NDIGPL ,10H NMAX ,10H NCYCLE ,/,2X,15.6X,I5,5(4X,I5),/) 423
270 FDRMAT (2X,10H DZO ,2X,10H DRO ,2X,10H ZMIN ,2X,10H 424
1 RMIN ,2X,10H MINDT ,2X,10H MAXDT ,2X,10H STAB ,2X,10 425
2H TZERO ,/,8(1X,E11.4),/) 426
280 FDRMAT (2X,10H RHDO ,2X,10H VZ ,2X,10H VR ,2X,10H 427
1 EO ,2X,10H BO ,2X,10H BR ,2X,10H BZ ,2X,10 428
2H PHI ,/,8(1X,E11.4),/) 429
290 FDRMAT (2X,10H VISCO ,2X,10H PERMO ,2X,10H MW ,2X,10H 430
1 ARFV ,/,4(1X,E11.4),/) 431
300 FDRMAT (3X,20H K1 J1 K2 J2 ,/,3X,4I5,/,10H RHDO ,10H 432
1 VZ ,10H VR ,10H EO ,10H BO ,10H BRO ,10 433
2H BZO ,10H PHIO ,/,1X,8E10.3,/,10H VISCO ,10H PERMO 434
3 ,/,1X,2E10.3,/) 435
310 FDRMAT (//,128(1H*),/,128(1H*),/,128(1H*)) 436
END 437
SUBROUTINE OUTPUT 438
C 439
C 440
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 441
C PRINTS OUTPUT FOR HYDRODYNAMIC, MAGNETIC, ELECTRIC AND VISCOUS 442
C PARAMETERS 443
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 444
C 445
C 446
COMMON /CARRAY/ RHD(45,225),U(45,225),V(45,225),E(45,225),PHI(45,

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1225),BD(1,1),BR(1,1),BZ(1,1),DE(1,1) 448
COMMON /COUTP/ TITLE(15),KPDEL,JPDEL,NPLDT,NPRN,NDIGPL,NGRAPH 449
COMMON /CMESH/ KMAX,JMAX,KP1,JP1,KP2,JP2 450
COMMON /CBOUND/ DANGLE(225),IDBK(225),IDBL(225),ISYM(4),IAXI,IDBO 451
COMMON /GRAVTY/ GC,GR,GZ 452
COMMON /CTIME/ TIME,DT,DTT,STAB,MINDT,MAXDT,NCYCLE,NMAX 453
COMMON/CGRID/R(45),RD(45),Z(225),DR(45),DZ(225),XD(45),ZMIN,RMIN,D 454
1 Z0,DRO,IGRAPH(225),NBOUND 455
COMMON /CCALC/ BL,EMF,MCALC,NMAGN,NTHRM,IPOT,IDFN,IPTSF 456
COMMON /CINIT/ RHO0,VZ,VR,B0,BRO,BZO,E0,PHI0,PERMO,VELDC,ARFV,PERM 457
1,NVECT,NPDIM 458
COMMON/CMHD/INSJ(225),DVOLT,BASEP,DPDT,SPACE,SPINSL,JPLMIN,JPLMAX 459
COMMON/CMATRIX/ ACDEF(225),BCDEF(225),CCDEF(225),DCDEF(225),SUB(225 460
1),DIAG(225),SUP(225),CONST(225) 461
COMMON/CSTRSS/TRRA(225),TZZA(225),TDDA(225),TRZA(225),VISC,VISCO 462
COMMON /CTAPE/ IRST 463
DIMENSION CON(52) 464
REAL*8 R,RD,RR 465
REAL JR,JZ,JR1,JZ1,INT,MINDT,MAXDT 466
DATA BFT,BFR,BFZ,BPHI/0.,0.,0.,0./ 467
C 468
C 469
POTN=0. 470
DO 10 KK=1,KP2 471
10 CON(KK)=0. 472
ATM=1.013*10.**6 473
WRITE (6,170) 474
WRITE (6,160) (TITLE(I),I=1,15) 475
C ***** 476
C ***** PRINTING HYDRODYNAMIC VARIABLES ***** 477
C ***** 478
DO 20 J=1,JP2,JPDEL 479
WRITE (6,150) Z(J),TIME,DT 480
WRITE (6,220) 481
WRITE (6,190) 482
WRITE (6,220) 483
DO 20 L=1,KP2,KPDEL 484
I=KP2+1-L 485
RR=R(I) 486
IF (IAXI.EQ.0) RR=R(I)-10.**5 487
INT=E(I,J)-0.5*(U(I,J)**2+V(I,J)**2) 488
GAMMA=GAMM(I,J) 489
P=(GAMMA-1.)*RHO(I,J)*INT 490
ZZ=Z(J) 491
CMACH=0. 492
CMACH=SQRT(GAMMA*ABS(P)/RHO(I,J)) 493
IF (CMACH.NE.0.) CMACH=(U(I,J)**2+V(I,J)**2)**0.5/CMACH 494
TEMP=(E(I,J)-0.5*(U(I,J)**2+V(I,J)**2))/CV(I,J,0,0) 495
P=P/(1.013*10.**6) 496
WRITE (6,180) J,I,RR,RHO(I,J),U(I,J),V(I,J),E(I,J),INT,P,TEMP,CMAC 497
1H 498
20 CONTINUE 499
IF (BL.EQ.0..AND.EMF.NE.1) GO TO 70 500
C ***** 501
C ***** PRINTING VISCOUS-MAGNETO (STRESS) VARIABLES ***** 502
C ***** 503
WRITE (6,170) 504
DO 60 J=1,JP2,JPDEL 505
WRITE (6,150) Z(J),TIME,DT 506
WRITE (6,220) 507
WRITE (6,200) 508
WRITE (6,220) 509
DO 60 L=1,KP2,KPDEL 510
I=KP2+1-L 511

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RR=R(I) 512
IF (IAXI.EQ.0) RR=R(I)-100000. 513
TZZIJ=0. 514
TRRIJ=0. 515
TDDIJ=0. 516
TRZIJ=0. 517
IF (I.EQ.KP2.DR.J.EQ.JP2) GO TO 40 518
IF (BL.EQ.2) GO TO 30 519
ERRIPH=(V(I+1,J)-V(I,J))/(R(I+1)-R(I)) 520
EZZJPH=(U(I,J+1)-U(I,J))/(Z(J+1)-Z(J)) 521
EDDIPH=(V(I+1,J)+V(I,J))/(R(I+1)+R(I)) 522
ERZIPH=(U(I+1,J)-U(I,J))/(R(I+1)-R(I)) 523
ERZJPH=(V(I,J+1)-V(I,J))/(Z(J+1)-Z(J)) 524
EEIJPH=EZZJPH+ERRIPH+EDDIPH 525
TRRIJ=(-2.*VISC*ERRIPH-2./3.*VISC*EEIJPH-BR(I,J)**2/PERM)/ATM 526
TZZIJ=(-2.*VISC*EZZJPH-2./3.*VISC*EEIJPH-BZ(I,J)**2/PERM)/ATM 527
TDDIJ=(-2.*VISC*EDDIPH-2./3.*VISC*EEIJPH-BD(I,J)**2/PERM)/ATM 528
TRZIJ=(VISC*(ERZIPH+ERZJPH)-BR(I,J)*BZ(I,J)/PERM)/ATM 529
30 IF (BL.EQ.1) GO TO 40 530
ERZPH=(U(I+1,J)-U(I,J))/(R(I+1)-R(I)) 531
TRZIJ=-EDDY(I,J)*ERZPH 532
40 CONTINUE 533
EDMU=EDDY(I,J)+VISC 534
IF (EMF.NE.1.) GO TO 50 535
BFO=BD(I,J) 536
BFR=BR(I,J) 537
BFZ=BZ(I,J) 538
50 CONTINUE 539
WRITE (6,180) J,I,RR,BFO,BFR,BFZ,EDMU,TZZIJ,TRRIJ,TDDIJ,TRZIJ 540
1,TRZIJ 541
60 CONTINUE 542
70 CONTINUE 543
IF (EMF.LT.2.) GO TO 100 544
C ***** 545
C ***** PRINTING ELECTRICAL VARIABLES ***** 546
C ***** 547
WRITE (6,170) 548
DO 90 J=1,JP2,JPDEL 549
WRITE (6,220) 550
WRITE (6,210) 551
WRITE (6,220) 552
DO 90 L=1,KP2,KPDEL 553
I=KP2+1-L 554
RR=R(I) 555
IF (IAXI.EQ.0) RR=R(I)-100000. 556
JR=0 557
JZ=0 558
IF (I.EQ.1.DR.I.EQ.KP2.DR.J.EQ.1.DR.J.EQ.JP2) GO TO 80 559
IF (J.EQ.2) POTN=0. 560
UU=U(I,J) 561
VV=V(I,J) 562
CALL CURRNT (JZ,JR,EZ,ER,UU,VV,I,J,0,0) 563
UU=U(I,J-1) 564
VV=V(I,J-1) 565
JM=J-1 566
CALL CURRNT (JZ1,JR1,EZ1,ER1,UU,VV,I,JM,0,0) 567
CON(I)=POTN 568
POTN=CON(I)-(JR+JR1)/2.*(Z(J)-Z(J-1)) 569
IF (IPTSF.EQ.1) POTN=CON(I)-(EZ+EZ1)/2.*(Z(J)-Z(J-1)) 570
PVOLT=PHI(I,J)*10.**(-8) 571
IF (IPTSF.NE.2) PVOLT=POTN*10.**(-8) 572
PSI=PHI(I,J) 573
IF (IPTSF.EQ.2) PSI=POTN 574
80 CONTINUE 575

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SIGG=SIG(I,J,0,0,0) 576
BETT=BETA(I,J,0,0) 577
RGAG=RGAS(P,T) 578
T=(E(I,J)-0.5*(U(I,J)**2+V(I,J)**2))/CV(I,J,0,0) 579
BB=B(I,J) 580
WRITE (6,180) J,I,PVOLT,PSI,BB,BETT,SIGG,JZ,JR,EZ,ER 581
90 CONTINUE 582
100 CONTINUE 583
IF (NDIGPL.NE.0) CALL DIGPLT 584
C ***** 585
C ***** RESTART TAPE ***** 586
C ***** 587
IF (MOD(NCYCLE,NPRN).NE.0) GO TO 130 588
IF (IRST.EQ.0) GO TO 130 589
REWIND 15 590
WRITE (6,140) IRST,NCYCLE,TIME 591
TZERO=TIME 592
IRST=IRST+1 593
IF (IRST.EQ.0) IRST=1 594
LMAX=NMAX+NPRN 595
WRITE (15) IRST,NCYCLE,TIME,DT 596
DO 120 IZ=1,JP2 597
DO 120 IX=1,KP2 598
IF (EMF.EQ.2.) PHI(IX,IZ)=BPHI 599
IF (EMF.NE.1.) GO TO 110 600
BQ(IX,IZ)=BFT 601
BR(IX,IZ)=BFR 602
BZ(IX,IZ)=BFZ 603
110 CONTINUE 604
120 CONTINUE 605
130 CONTINUE 606
RETURN 607
C 608
C 609
C 610
140 FORMAT (1X,120(1HX),/,25X,14HRESTART TAPE ,13,2X,10HFOR CYCLE ,15 611
1,2X,8HAT TIME ,E12.4,4H SEC,/,1X,120(1HX)) 612
150 FORMAT (/,25X,5HZ = ,E12.4,5X,7HTIME = ,E12.4,5X,5HOT = ,E12.4,/) 613
160 FORMAT (25X,15A4,/) 614
170 FORMAT (1H1) 615
180 FORMAT (2(2X,13),9(1X,E12.5)) 616
190 FORMAT (2X,3H J ,2X,3H I ,13H R ,13H DENSITY ,13H 617
1VELDC-Z ,13H VELDC-R ,13H TOT ENERGY ,13H INT ENERGY ,13H 618
2 PRESSURE ,13H TEMPERATURE ,13H MACH NO ,/,10X,13H CM 619
3 ,13H GM/CM3 ,13H CM/SEC ,13H CM/SEC ,13H ERG/G 620
4M ,13H ERG/GM ,13H ATMOSPHERES ,13H DEGREE K ,13H - 621
5-- ,/) 622
200 FORMAT (2X,3H J ,2X,3H I ,13H R ,13H B ,13H 623
1 BR ,13H BZ ,13H EDDY+VISC ,13H TZZ ,13H 624
2 TRR ,13H TOD ,13H TRZ ,/,10X,13H CM 625
3 ,13H GAUSS ,13H GAUSS ,13H GAUSS ,13H GM/CM- 626
4SEC ,13H ATM ,13H ATM ,13H ATM ,13H A 627
5TM ,/) 628
210 FORMAT (2X,3H J ,2X,3H I ,13H POTENTIAL ,13H STREAM FNCT ,13H 629
1 B ,13H BETA ,13H ELECT COND ,13H JZ ,13H 630
2 JR ,13H EZ ,13H ER ,/,10X,13H VOLTS*E8 631
3 ,13H AMP/CM38 ,13H GAUSS ,13H ,13H MHD/M E 632
411 ,13H AMP/CM2 ,13H AMP/CM2 ,13H GAUSSCM/SEC ,13HGAUSS 633
5CM/SEC ) 634
220 FORMAT (2X,124(1H*)) 635
END 636
SUBROUTINE GRAPH 637
C 638
C 639

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C      XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX      640
C      WRITES TO DISK VALUES OF ALL VARIABLES FOR ALL CELLS INORDER              641
C      FOR PLOTTING LATER                                                            642
C      XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX      643
C                                                                                     644
C                                                                                     645
COMMON /CARRAY/ RHO(45,225),U(45,225),V(45,225),E(45,225),PHI(45,
1225),BO(1,1),BR(1,1),BZ(1,1),DE(1,1)
646
COMMON /CMESH/ KMAX,JMAX,KP1,JP1,KP2,JP2
648
COMMON /CBOUND/ DANGLE(225),IOBK(225),IOBL(225),ISYM(4),IAXI,IOBQ
649
COMMON /GRAVITY/ GC,GR,GZ
650
COMMON /CTIME/ TIME,DT,DTT,STAB,MINDT,MAXDT,NCYCLE,NMAX
651
COMMON /CGRID/R(45),RD(45),Z(225),DR(45),DZ(225),XD(45),ZMIN,RMIN,D
652
1ZO,DRO,IGRAPH(225),NBOUND
653
COMMON /CCALC/ BL,EMF,MCALC,NMAGN,NTHRM,IPDT,IDFN,IPTSF
654
COMMON /CSTRSS/TRRA(225),TZZA(225),TDDA(225),TRZA(225),VISC,VISCO
655
COMMON /CINIT/ RHDO,VZ,VR,BO,BRO,BZO,EO,PHIO,PERMO,VELOC,ARFV,PERM
656
1,NVECT,NPDIM
657
COMMON /CMHD/INSJ(225),DVOLT,BASEP,DPOT,SPACE,SPINSL,JPLMIN,JPLMAX
658
COMMON /CMATRX/ ACDEF(225),BCDEF(225),CCDEF(225),DCDEF(225),SUB(225
659
1),DIAG(225),SUP(225),CONST(225)
660
DIMENSION DUMVAR(50),DNM(525),CON(52)
661
COMMON /TPLT/ TPLTMI,TPLTMA,TPLTDE,TPLTOL,TZERO,T
662
REAL *8 R,RD
663
REAL JR,JZ,JR1,JZ1,INT
664
C                                                                                     665
C      *****
666
C      ***** SUBROUTINE RDPLT CONTAINS A VARIABLE LIST *****
667
C      *****
668
PDTN=0.
669
GAMMA=GAMM(1,1)
670
LBJ=0
671
NUM=KP2*JP2
672
RIMH=0.
673
DO 110 I=1,KP2
674
DO 110 J=1,JP2
675
DO 10 L=01,36
676
10 DUMVAR(L)=0.
677
RIPH=R(I)+DR(I)/2.
678
IF (I.EQ.1) GO TO 20
679
RIMH=R(I-1)+DR(I)/2.
680
20 LBJ=LBJ+1
681
C      *****
682
C      ***** ASSIGNS VALUES OF CELL (I,J) TO DUMVAR ARRAY *****
683
C      *****
684
DUMVAR(1)=I
685
DUMVAR(2)=J
686
Y=R(I)
687
IF (IAXI.EQ.0) Y=R(I)-10000.
688
DUMVAR(3)=Y
689
DUMVAR(4)=Z(J)
690
DUMVAR(5)=DR(I)
691
DUMVAR(6)=DZ(J)
692
DUMVAR(7)=U(I,J)
693
DUMVAR(8)=V(I,J)
694
INT=E(I,J)-0.5*(U(I,J)**2+V(I,J)**2)
695
DUMVAR(9)=(GAMMA-1.)*RHO(I,J)*INT
696
DUMVAR(10)=E(I,J)
697
DUMVAR(11)=INT
698
DUMVAR(12)=SQRT(GAMMA*ABS(DUMVAR(9))/RHO(I,J))
699
IF (DUMVAR(9).NE.0.) DUMVAR(13)=(U(I,J)**2+V(I,J)**2)**0.5/SQRT(GA
700
IMMA*ABS(DUMVAR(9))/RHO(I,J))
701
DUMVAR(14)=RHO(I,J)
702
DUMVAR(15)=3.1416*RHO(I,J)*(RIPH**2-RIMH**2)*DZ(J)
703

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IF (EMF.EQ.1.) DUMVAR(16)=BD(I,J)	704
IF (I.EQ.KP2.DR.J.EQ.JP2) GO TO 40	705
ERRIPH=(V(I+1,J)-V(I,J))/(R(I+1)-R(I))	706
EZZJPH=(U(I,J+1)-U(I,J))/(Z(J+1)-Z(J))	707
EDDIPH=(V(I+1,J)+V(I,J))/(R(I+1)+R(I))	708
ERZIPH=(U(I+1,J)-U(I,J))/(R(I+1)-R(I))	709
ERZJPH=(V(I,J+1)-V(I,J))/(Z(J+1)-Z(J))	710
EEIJPH=EZZJPH+ERRIPH+EDDIPH	711
TRRIJ=-2.*VISC*ERRIPH-2./3.*EEIJPH	712
TZZIJ=-2.*VISC*EZZJPH-2./3.*EEIJPH	713
TDDIJ=-2.*VISC*EDDIPH-2./3.*EEIJPH	714
TRZIJ=VISC*(ERZIPH+ERZJPH)	715
IF (EMF.NE.1.) GO TO 30	716
TRRIJ=TRRIJ+BR(I,J)**2/PERM	717
TZZIJ=TZZIJ+BZ(I,J)**2/PERM	718
TDDIJ=TDDIJ+BD(I,J)**2/PERM	719
TRZIJ=TRZIJ+BR(I,J)*BZ(I,J)/PERM	720
30 CONTINUE	721
DUMVAR(17)=TRRIJ	722
DUMVAR(18)=TZZIJ	723
DUMVAR(19)=TDDIJ	724
DUMVAR(20)=TRZIJ	725
40 CONTINUE	726
DUMVAR(21)=TIME	727
DUMVAR(22)=DT	728
DUMVAR(23)=VISC	729
IF (EMF.EQ.1.) DUMVAR(24)=BR(I,J)	730
IF (EMF.EQ.1.) DUMVAR(25)=BZ(I,J)	731
IF (EMF.EQ.0.) GO TO 50	732
JZ=0	733
JR=0	734
IF (I.EQ.1.DR.I.EQ.KP2.DR.J.EQ.1.DR.J.EQ.JP2) GO TO 50	735
IF (J.EQ.2) POTN=0.	736
UU=U(I,J)	737
VV=V(I,J)	738
CALL CURRNT (JZ,JR,EZ,ER,UU,VV,I,J,0,0)	739
UU=U(I,J-1)	740
VV=V(I,J-1)	741
JM=J-1	742
CALL CURRNT (JZ1,JR1,EZ1,ER1,UU,VV,I,JM,0,0)	743
DUMVAR(26)=JR	744
DUMVAR(27)=JZ	745
DUMVAR(19)=(JR-BETA(I,J,0,0)*JZ)/SIG(I,J,0,0)+U(I,J)*B(I,J)	746
DUMVAR(20)=(JZ+BETA(I,J,0,0)*JR)/SIG(I,J,0,0)-V(I,J)*B(I,J)	747
CON(I)=POTN	748
POTN=CON(I)-(JR+JR1)/2.*(Z(J)-Z(J-1))	749
IF (IPTSF.EQ.1) POTN=CON(I)-(EZ+EZ1)/2.*(Z(J)-Z(J-1))	750
50 CONTINUE	751
GAMMA=GAMM(I,J)	752
DUMVAR(28)=GAMMA	753
SI=SIG(I,J,0,0)	754
DUMVAR(29)=SI	755
SIGMA=5.668*10.**(-5)	756
DUMVAR(30)=0.	757
KOBL=KP2+1-IDBL(J)	758
IF (I.GE.IDBL(J)) DUMVAR(30)=2.	759
IF (NVECT.EQ.1) GO TO 60	760
IF (I.LE.KOBL) DUMVAR(30)=2.	761
60 CONTINUE	762
CVV=CV(I,J,0,0)	763
DUMVAR(31)=INT/ CVV	764
IF (EMF.NE.2.) GO TO 65	765
PVOLT=PHI(I,J)*10.**(-8)	766
IF (IPTSF.NE.2) PVOLT=POTN*10.**(-8)	767

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PSI=PHI(I,J) 768
IF (IPTSF.EQ.2) PSI=POTN 769
DUMVAR(32)=PVOLT 770
DUMVAR(33)=PSI 771
BET=BETA(I,J,0,0) 772
DUMVAR(34)=BET 773
DUMVAR(35)=COND(I,J,0,0) 774
65 CONTINUE 775
IF (I.GT.1.AND.I.LT.KP2.AND.J.GT.1.AND.J.LT.JP2) DUMVAR(36)=(U(I+1 776
I,J)-U(I-1,J))/(2.*DR(I))+V(I,J+1)-V(I,J-1))/(2.*DZ(J)) 777
DUMVAR(9)=DUMVAR(9)/(1.013**10.**6) 778
IF (LBJ.EQ.1) INUMB=0 779
IND=INUMB*36 780
DO 70 MIN=1,36 781
IND=INUMB*36+MIN 782
70 DNM(IND)=DUMVAR(MIN) 783
INUMB=INUMB+1 784
IF (I.EQ.KP2.AND.J.EQ.JP2) INUMB=0 785
IF (INUMB.EQ.14) INUMB=0 786
IF (I.LT.KP2.DR.J.LT.JP2) GO TO 90 787
LM1=IND+1 788
C ***** 789
C ***** WRITES TO DISK (UNIT 14) BLOCKED DATA OF THE ***** 790
C ***** CELL PARAMETER VALUES ***** 791
C ***** 792
DO 80 LM=LM1,504 793
80 DNM(LM)=0. 794
90 IF (INUMB.GT.0) GO TO 100 795
WRITE (14) (DNM(KX),KX=1,504),TIME,NCYCLE,DT 796
T=TIME 797
100 CONTINUE 798
IF (I.EQ.KP2.AND.J.EQ.JP2) PRINT 120,TIME,NCYCLE 799
110 CONTINUE 800
RETURN 801
C 802
C 803
C 804
120 FORMAT (12H T,NCYCLE ,2X,E12.4,2X,I5) 805
END 806
SUBROUTINE DIGPLT 807
C 808
C 809
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 810
C GENERATES DIGITAL PLOTS 811
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 812
C 813
C 814
COMMON /CARRAY/ RHO(45,225),U(45,225),V(45,225),E(45,225),PHI(45, 815
1225),BO(1,1),BR(1,1),BZ(1,1),DE(1,1) 816
COMMON /CMESH/ KMAX,JMAX,KP1,JP1,KP2,JP2 817
COMMON /CBOUND/ DANGLE(225),IOBK(225),IOBL(225),ISYM(4),IAXI,IOBQ 818
COMMON /GRAVTY/ GC,GR,GZ 819
COMMON /CTIME/ TIME,DT,DTT,STAB,MINDT,MAXDT,NCYCLE,NMAX 820
COMMON /CGRID/ R(45),RD(45),Z(225),DR(45),DZ(225),XD(45),ZMIN,RMIN,D 821
120,DRO,IGRAPH(225),NBOUND 822
COMMON /CCALC/ BL,EMF,MCALC,NMAGN,NTHRM,IPOT,IDFN,IPTSF 823
COMMON /CINIT/ RHDO,VZ,VR,BO,BRO,BZO,EO,PHIO,PERMO,VELOC,ARFV,PERM 824
1,NVECT,NPDIM 825
COMMON /CMHD/ INSJ(225),DVOLT,BASEP,DPOT,SPACE,SPINSL,JPLMIN,JPLMAX 826
COMMON /CMATRIX/ ACDEF(225),BCDEF(225),CCDEF(225),DCDEF(225),SUB(225 827
1),DIAG(225),SUP(225),CONST(225) 828
DIMENSION IPLT(132) 829
REAL*8 R,RD 830
REAL JR,JZ,JZMIN,JZMAX,JRMIN,JRMAX,INT 831

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JDIFF=1+JP1/120
DO 40 L=1, KP2, JDIFF
K=KP2-L+1
M=0
DO 30 J=1, JP2, JDIFF
M=M+1
INT=E(K, J)-0.5*(U(K, J)**2+V(K, J)**2)
P=(GAMMA-1.)*RHO(K, J)*INT
IF (RHO(K, J).NE.0.) CMACH=SQRT(GAMMA*ABS(P)/RHO(K, J))
IF (CMACH.NE.0.) CMACH=(U(K, J)**2+V(K, J)**2)**0.5/CMACH
P=P/ATM
T=INT/CV(K, J, 0, 0)
C *****
C ***** INTERPOLATING BETWEEN MAX AND MIN *****
C *****
IF (KJ.EQ.1) IPLT(M)=(P-PMIN)/(PMAX-PMIN)*9.9
IF (KJ.EQ.2) IPLT(M)=(CMACH-CMIN)/(CMAX-CMIN)*9.9
IF (KJ.EQ.3) IPLT(M)=(RHO(K, J)-RMIN)/(RMAX-RMIN)*9.9
IF (KJ.EQ.4) IPLT(M)=(T-TMIN)/(TMAX-TMIN)*9.9
IF (KJ.EQ.5) IPLT(M)=(U(K, J)-UMIN)/(UMAX-UMIN)*9.9
IF (KJ.EQ.6) IPLT(M)=(V(K, J)-VMIN)/(VMAX-VMIN)*9.9
KOBL=KP2+1-IDBL(J)
IF (K.GE.IDBL(J)) IPLT(M)=-1
IF (NVECT.EQ.1) GO TO 30
IF (K.LE.KOBL) IPLT(M)=-1
30 CONTINUE
N=JP2/JDIFF
CALL PRTPLT (IPLT, N)
40 CONTINUE
50 CONTINUE
IF (EMF.NE.2.) GO TO 170
JZMIN=10.***12
JRMIN=10.***12
JZMAX=-10.***12
JRMAX=-10.***12
PHIMIN=PHI(1, 1)
PHIMAX=PHI(1, 1)
SIGMIN=+10.***6
SIGMAX=-10.***6
BETMIN=+10.***6
BETMAX=-10.***6
BMIN=10.***7
BMAX=-10.***7
C *****
C ***** SEEKING MINIMUM/MAXIMUM FOR CURRENTS, TEMPERATURE *****
C *****
C ***** HALL PARAMETER, ELECTRIC CONDUCTION AND *****
C ***** POTENTIAL OR STREAM FUNCTION *****
C *****
DO 90 K=1, KP2
DO 90 J=1, JP2
IF (K.EQ.1.DR.K.EQ.KP2.DR.J.EQ.1.DR.J.EQ.JP2) GO TO 80
I=K
IF (IPTSF.NE.2) GO TO 60
DPHIDZ=(PHI(K, J+1)-PHI(K, J-1))/(Z(J+1)-Z(J-1))
DPHIDR=(PHI(K+1, J)-PHI(K-1, J))/(R(K+1)-R(K-1))
JZ=SIG(I, J, 0, 0, 1)*((-DPHIDZ+V(I, J)*B(I, J))-BETA(I, J, 0, 0)*(-DPHIDR-
1U(I, J)*B(I, J)))
JR=SIG(I, J, 0, 0, 1)*(BETA(I, J, 0, 0)*(-DPHIDZ+V(I, J)*B(I, J))+(-DPHIDR-
1U(I, J)*B(I, J)))
GO TO 70
60 JZ=(PHI(I+1, J)-PHI(I-1, J))/(2.*DR(I))
JR=-(PHI(I, J+1)-PHI(I, J-1))/(2.*DZ(J))
70 CONTINUE
JZMIN=AMINI(JZMIN, JZ)

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JZMAX=AMAX1(JZMAX, JZ) 960
JRMIN=AMINI(JRMIN, JR) 961
JRMAX=AMAX1(JRMAX, JR) 962
80 SIGMIN=AMINI(SIG(K, J, 0, 0, 0), SIGMIN) 963
SIGMAX=AMAX1(SIG(K, J, 0, 0, 0), SIGMAX) 964
BETMIN=AMINI(BETA(K, J, 0, 0), BETMIN) 965
BETMAX=AMAX1(BETA(K, J, 0, 0), BETMAX) 966
IF (EMF.EQ.1.) BP=(BD(K, J)**2/PERM+BR(K, J)**2/PERM+BZ(K, J)**2/PERM
1)/ATM/2. 967
IF (EMF.NE.1.) BP=B(K, J)**2/PERM/ATM 968
BMIN=AMINI(BMIN, BP) 969
BMAX=AMAX1(BMAX, BP) 970
PHIMIN=AMINI(PHIMIN, PHI(K, J)) 971
PHIMAX=AMAX1(PHIMAX, PHI(K, J)) 972
90 CONTINUE 973
DO 160 KJ=7, 12 974
IF (KJ.EQ.7.AND.JZMIN.EQ.JZMAX) GO TO 160 975
IF (KJ.EQ.8.AND.JRMIN.EQ.JRMAX) GO TO 160 976
IF (KJ.EQ.9.AND.PHIMIN.EQ.PHIMAX) GO TO 160 977
IF (KJ.EQ.10.AND.SIGMIN.EQ.SIGMAX) GO TO 160 978
IF (KJ.EQ.11.AND.BETMIN.EQ.BETMAX) GO TO 160 979
IF (KJ.EQ.12.AND.BMIN.EQ.BMAX) GO TO 160 980
WRITE (6, 180) 981
IF (KJ.EQ.7) WRITE (6, 250) JZMIN, JZMAX 982
IF (KJ.EQ.8) WRITE (6, 260) JRMIN, JRMAX 983
PVL TMI=PHIMIN 984
PVL TMA=PHIMAX 985
IF (IPTSF.EQ.2) PVL TMI=PVL TMI*10.**(-8) 986
IF (IPTSF.EQ.2) PVL TMA=PVL TMA*10.**(-8) 987
IF (KJ.EQ.9) WRITE (6, 270) PVL TMI, PVL TMA 988
IF (KJ.EQ.10) WRITE (6, 280) SIGMIN, SIGMAX 989
IF (KJ.EQ.11) WRITE (6, 290) BETMIN, BETMAX 990
IF (KJ.EQ.12) WRITE (6, 220) BMIN, BMAX 991
DO 100 NX=1, 125 992
IPLT(NX)=0 993
100 IF (NX.GT.105.AND.NX.LT.116) IPLT(NX)=NX-106 994
CALL PRTPLT (IPLT, 115) 995
JDIFF=1+JP1/120 996
DO 150 L=1, KP2, JDIFF 997
K=KP2-L+1 998
M=0 999
DO 140 J=1, JP2, JDIFF 1000
M=M+1 1001
IF (K, EQ.1.DR, K, EQ. KP2.DR, J, EQ.1.DR, J, EQ. JP2) GO TO 130 1002
I=K 1003
IF (IPTSF.NE.2) GO TO 110 1004
DPHIDZ=(PHI(K, J+1)-PHI(K, J-1))/(Z(J+1)-Z(J-1)) 1005
DPHIDR=(PHI(K+1, J)-PHI(K-1, J))/(R(K+1)-R(K-1)) 1006
JZ=SIG(K, J, 0, 0, 1)**(-DPHIDZ+V(K, J)**B(K, J))-BETA(K, J, 0, 0)**(-DPHIDR-
1U(K, J)**B(K, J)) 1007
JR=SIG(K, J, 0, 0, 1)**(BETA(K, J, 0, 0)**(-DPHIDZ+V(K, J)**B(K, J)))+(DPHIDR-
1U(K, J)**B(K, J)) 1008
GO TO 120 1009
110 JZ=(PHI(I+1, J)-PHI(I-1, J))/(2.*DR(I)) 1010
JR=(PHI(I, J+1)-PHI(I, J-1))/(2.*DZ(J)) 1011
120 CONTINUE 1012
C ***** 1016
C ***** INTERPOLATING BETWEEN MAX AND MIN ***** 1017
C ***** 1018
IF (KJ.EQ.7) IPLT(M)=(JZ-JZMIN)/(JZMAX-JZMIN)*9.9 1019
IF (KJ.EQ.8) IPLT(M)=(JR-JRMIN)/(JRMAX-JRMIN)*9.9 1020
130 IF (KJ.EQ.9) IPLT(M)=(PHI(K, J)-PHIMIN)/(PHIMAX-PHIMIN)*9.9 1021
IF (KJ.EQ.10) IPLT(M)=(SIG(K, J, 0, 0, 0)-SIGMIN)/(SIGMAX-SIGMIN)*9.9 1022
IF (KJ.EQ.11) IPLT(M)=(BETA(K, J, 0, 0)-BETMIN)/(BETMAX-BETMIN)*9.9 1023

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IF (EMF.EQ.1.) BP=(BO(K,J)**2/PERM+BR(K,J)**2/PERM+BZ(K,J)**2/PERM
1)/ATM/2. 1024
IF (EMF.NE.1.) BP=B(K,J)**2/PERM/ATM 1025
IF (KJ.EQ.12) IPLT(M)=(BP-BMIN)/(BMAX-BMIN)*9.9 1026
IF (KJ.EQ.9.DR.KJ.EQ.12) GO TO 140 1027
IF (K.EQ.1.DR.K.EQ.KP2) GO TO 150 1028
KDBL=KP2+1-IDBL(J) 1029
IF (K.LE.KDBL) IPLT(M)=-1 1030
IF (NVECT.EQ.1) GO TO 140 1031
IF (K.GE.IDBL(J)) IPLT(M)=-1 1032
140 CONTINUE 1033
N=JP2/JDIFF 1034
CALL PRTPLT (IPLT,N) 1035
150 CONTINUE 1036
160 CONTINUE 1037
170 CONTINUE 1038
RETURN 1039
1040
C 1041
C 1042
C 1043
180 FORMAT (////) 1044
190 FORMAT (20X,12H PRESSURE .5X,4H MIN,1X,E12.4,5X,4HMAX ,E12.4,10X
1.11HATMOSPHERES,/) 1045
200 FORMAT (20X,12H MACH NO .5X,4H MIN,1X,E12.4,5X,4HMAX ,E12.4,10X
1.11H DMLS ,/) 1046
210 FORMAT (20X,12H DENSITY .5X,4H MIN,1X,E12.4,5X,4HMAX ,E12.4,10X
1.11H GM/CM3 ,/) 1047
220 FORMAT (20X,12H MAGN PRESS .5X,4H MIN,1X,E12.4,5X,4HMAX ,E12.4,10X
1.11HATMOSPHERES,/) 1048
230 FORMAT (20X,12HAXIAL-VELDC .5X,4H MIN,1X,E12.4,5X,4HMAX ,E12.4,10X
1.11H CM/SEC ,/) 1049
240 FORMAT (20X,12HRADIAL-VELDC,5X,4H MIN,1X,E12.4,5X,4HMAX ,E12.4,10X
1.11H CM/SEC ,/) 1050
250 FORMAT (20X,12H CURRENT - Z,5X,4H MIN,1X,E12.4,5X,4HMAX ,E12.4,10X
1.11HABCDUL/SEC ,/) 1051
260 FORMAT (20X,12H CURRENT - R,5X,4H MIN,1X,E12.4,5X,4HMAX ,E12.4,10X
1.11HABCDUL/SEC ,/) 1052
270 FORMAT (20X,12H PHI DR PSI .5X,4H MIN,1X,E12.4,5X,4HMAX ,E12.4,10X
1.11H ,/) 1053
280 FORMAT (20X,12HCONDUCTIVITY,5X,4H MIN,1X,E12.4,5X,4HMAX ,E12.4,10X
1.11HMHO/M E11 ,/) 1054
290 FORMAT (20X,12HHALL PARAMTR,5X,4H MIN,1X,E12.4,5X,4HMAX ,E12.4,10X
1.11H DMLS ,/) 1055
300 FORMAT (20X,12H TEMPERATURE,5X,4H MIN,1X,E12.4,5X,4HMAX ,E12.4,10X
1.11H DEG K ,/) 1056
END 1057
SUBROUTINE PRTPLT (A,N) 1058
1059
C 1060
C 1061
C 1062
C 1063
C 1064
C 1065
C 1066
C 1067
C 1068
C 1069
C 1070
C 1071
C 1072
C 1073
C 1074
C 1075
C 1076
C 1077
C 1078
C 1079
C 1080
C 1081
C 1082
C 1083
C 1084
C 1085
C 1086
C 1087
DD 10 I=1,132
10 B(I)=BLANK
DD 20 I=1,N

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IF (A(I).EQ.-1) B(I)=DOT	1088
IF (A(I).EQ.1) B(I)=ONE	1089
IF (A(I).EQ.2) B(I)=TWO	1090
IF (A(I).EQ.3) B(I)=THREE	1091
IF (A(I).GE.4) B(I)=FOUR	1092
20 CONTINUE	1093
WRITE (6,130) B	1094
DO 30 I=1,132	1095
30 B(I)=BLANK	1096
DO 40 I=1,N	1097
IF (A(I).LT.4) GO TO 40	1098
IF (A(I).EQ.4) B(I)=SEVEN	1099
IF (A(I).EQ.5) B(I)=TWO	1100
IF (A(I).GE.6) B(I)=THREE	1101
FLAG=1	1102
40 CONTINUE	1103
IF (FLAG.EQ.0) GO TO 120	1104
WRITE (6,140) B	1105
FLAG=0	1106
DO 50 I=1,132	1107
50 B(I)=BLANK	1108
DO 60 I=1,N	1109
IF (A(I).LT.7) GO TO 60	1110
IF (A(I).EQ.7) B(I)=SEVEN	1111
IF (A(I).GE.8) B(I)=FIVE	1112
FLAG=1	1113
60 CONTINUE	1114
IF (FLAG.EQ.0) GO TO 120	1115
WRITE (6,140) B	1116
FLAG=0	1117
DO 70 I=1,132	1118
70 B(I)=BLANK	1119
DO 80 I=1,N	1120
IF (A(I).LT.8) GO TO 80	1121
IF (A(I).EQ.8) B(I)=THREE	1122
IF (A(I).EQ.9) B(I)=SIX	1123
FLAG=1	1124
80 CONTINUE	1125
IF (FLAG.EQ.0) GO TO 120	1126
WRITE (6,140) B	1127
FLAG=0	1128
DO 90 I=1,132	1129
90 B(I)=BLANK	1130
DO 110 I=1,3	1131
DO 100 J=1,N	1132
IF (A(J).NE.9) GO TO 100	1133
B(J)=SPECCH(I)	1134
FLAG=1	1135
100 CONTINUE	1136
IF (FLAG.EQ.0) GO TO 120	1137
WRITE (6,140) B	1138
110 CONTINUE	1139
120 RETURN	1140
C	1141
C	1142
C	1143
130 FORMAT (1H,132A1)	1144
140 FORMAT (1H+,132A1)	1145
END	1146
SUBROUTINE GEDM	1147
C	1148
C	1149
C	1150
C	1151
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX	
SETS UP GRID GEOMETRY BY SPACING CELLS AT INTERVALS OF (DR,DZ)	

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C      XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX      1152
C      1153
C      1154
C      COMMON /CMESH/ KMAX, JMAX, KP1, JP1, KP2, JP2      1155
C      COMMON/CGRID/R(45), RD(45), Z(225), DR(45), DZ(225), XD(45), ZMIN, RMIN, D      1156
C      IZO, DRO, IGRAPH(225), NBOUND      1157
C      COMMON /CBOUND/ DANGLE(225), IOBK(225), IOBL(225), ISYM(4), IAXI, IOBO      1158
C      REAL*8 R, RD      1159
C      1160
C      1161
C      DZ(1)=DZO      1162
C      DR(1)=DRO      1163
C      Z(1)=ZMIN+DZ(1)/2.      1164
C      R(1)=RMIN+DR(1)/2.      1165
C      IF (IAXI.EQ.0) R(1)=R(1)+100000.      1166
C      DO 10 I=2, KP2      1167
C      DR(I)=DRO      1168
C      10 R(I)=R(I-1)+(DR(I)+DR(I-1))/2.      1169
C      DO 20 J=2, JP2      1170
C      DZ(J)=DZO      1171
C      20 Z(J)=Z(J-1)+(DZ(J)+DZ(J-1))/2.      1172
C      RETURN      1173
C      END      1174
C      SUBROUTINE BOUND      1175
C      1176
C      1177
C      XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX      1178
C      BOUNDARY VALUES ASSIGNED AT BOTTOM, LEFT, TOP AND RIGHT FACES      1179
C      XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX      1180
C      1181
C      1182
C      COMMON /CARRAY/ RHO(45,225), U(45,225), V(45,225), E(45,225), PHI(45,      1183
C      1225), BO(1,1), BR(1,1), BZ(1,1), DE(1,1)      1184
C      COMMON /CMESH/ KMAX, JMAX, KP1, JP1, KP2, JP2      1185
C      COMMON /CBOUND/ DANGLE(225), IOBK(225), IOBL(225), ISYM(4), IAXI, IOBO      1186
C      COMMON /GRAVTY/ GC, GR, GZ      1187
C      COMMON /CTIME/ TIME, DT, DTT, STAB, MINDT, MAXDT, NCYCLE, NMAX      1188
C      COMMON/CGRID/R(45), RD(45), Z(225), DR(45), DZ(225), XD(45), ZMIN, RMIN, D      1189
C      IZO, DRO, IGRAPH(225), NBOUND      1190
C      COMMON /CCALC/ BL, EMF, MCALC, NMAGN, NTHRM, IPOT, IDFN, IPTSF      1191
C      COMMON /CINIT/ RHDO, VZ, VR, BO, BRO, BZO, EO, PHIO, PERMO, VELOC, ARFV, PERM      1192
C      I, NVECT, NPDIM      1193
C      COMMON/CMHD/INSJ(225), DVOLT, BASEP, DPOT, SPACE, SPINSL, JPLMIN, JPLMAX      1194
C      COMMON/CMATRIX/ ACDEF(225), BCDEF(225), CCDEF(225), DCDEF(225), SUB(225      1195
C      I), DIAG(225), SUP(225), CONST(225)      1196
C      REAL*8 R, RD, RR, RDIST, ARG      1197
C      DATA ND/O/      1198
C      1199
C      1200
C      ISYM = 1 (BOTTOM), = 2 (LEFT), = 3 (TOP), = 4 (RIGHT)      1201
C      IF(ISYM( ) = +1 = TRANSMISSIVE, = -1 = REFLECTIVE      1202
C      IF(ISYM( ) = +2 = FIRST DERIVATIVES OF RHO,U,V AND P ARE CONSTANT      1203
C      KP3=KMAX+3      1204
C      JP3=JMAX+3      1205
C      *****      1206
C      1207
C      IF (ISYM(1).EQ.0) GO TO 20      1208
C      IP=ISYM(1)/IABS(ISYM(1))      1209
C      DO 10 J=1, JP2      1210
C      RHO(1, J)=RHO(2, J)+(RHO(2, J)-RHO(3, J))*(IABS(ISYM(1))-1)      1211
C      U(1, J)=+U(2, J)+(U(2, J)-U(3, J))*(IABS(ISYM(1))-1)      1212
C      V(1, J)=V(2, J)*IP+(V(2, J)-V(3, J))*(IABS(ISYM(1))-1)      1213
C      E(1, J)=E(2, J)+(E(2, J)-E(3, J))*(IABS(ISYM(1))-1)      1214
C      E(1, J)=E(1, J)-(U(2, J)**2+V(2, J)**2)/2. +(U(1, J)**2+V(1, J)**2)/2. -(

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1U(2, J)**2+V(2, J)**2)/2. -(U(3, J)**2+V(3, J)**2)/2.)*(IABS(ISYM(1))-1) 1216
2) 1217
C 1218
IF (EMF.NE.1.) GO TO 10 1219
BD(1, J)=BD(2, J)+(B(2, J)-B(3, J))*(IABS(ISYM(1))-1) 1220
BR(1, J)=BR(2, J)+(BR(2, J)-BR(3, J))*(IABS(ISYM(1))-1) 1221
BZ(1, J)=BZ(2, J)+(BZ(2, J)-BZ(3, J))*(IABS(ISYM(1))-1) 1222
10 CONTINUE 1223
C ***** 1224
20 IF (ISYM(2).EQ.0) GO TO 40 1225
IP=ISYM(2)/IABS(ISYM(2)) 1226
DO 30 K=1, KP2 1227
RHO(K, 1)=RHO(K, 2)+(RHO(K, 2)-RHO(K, 3))*(IABS(ISYM(2))-1) 1228
U(K, 1)=U(K, 2)*IP+(U(K, 2)-U(K, 3))*(IABS(ISYM(2))-1) 1229
V(K, 1)=V(K, 2)+(V(K, 2)-V(K, 3))*(IABS(ISYM(2))-1) 1230
E(K, 1)=E(K, 2)+(E(K, 2)-E(K, 3))*(IABS(ISYM(2))-1) 1231
E(K, 1)=E(K, 1)-(U(K, 2)**2+V(K, 2)**2)/2. +(U(K, 1)**2+V(K, 1)**2)/2. -( 1232
1U(K, 2)**2+V(K, 2)**2)/2. -(U(K, 3)**2+V(K, 3)**2)/2.)*(IABS(ISYM(1))-1) 1233
2) 1234
C 1235
IF (EMF.NE.1.) GO TO 30 1236
BD(K, 1)=BD(K, 2)+(BD(K, 2)-BD(K, 3))*(IABS(ISYM(2))-1) 1237
BR(K, 1)=BR(K, 2)+(BR(K, 2)-BR(K, 3))*(IABS(ISYM(2))-1) 1238
BZ(K, 1)=BZ(K, 2)+(BZ(K, 2)-BZ(K, 3))*(IABS(ISYM(2))-1) 1239
30 CONTINUE 1240
C ***** 1241
C 1242
40 IF (ISYM(3).EQ.0) GO TO 60 1243
IP=ISYM(3)/IABS(ISYM(3)) 1244
DO 50 J=1, JP2 1245
RHO(KP2, J)=RHO(KP1, J)+(RHO(KP1, J)-RHO(KMAX, J))*(IABS(ISYM(3))-1) 1246
U(KP2, J)=U(KP1, J)+(U(KP1, J)-U(KMAX, J))*(IABS(ISYM(3))-1) 1247
V(KP2, J)=V(KP1, J)*IP+(V(KP1, J)-V(KMAX, J))*(IABS(ISYM(3))-1) 1248
E(KP2, J)=E(KP1, J)+(E(KP1, J)-E(KMAX, J))*(IABS(ISYM(3))-1) 1249
E(KP2, J)=E(KP2, J)-(U(KP1, J)**2+V(KP1, J)**2)/2. +(U(KP2, J)**2+V(KP2, 1250
1, J)**2)/2. -(U(KP1, J)**2+V(KP1, J)**2)/2. -(U(KMAX, J)**2+V(KMAX, J)**2) 1251
2)/2.)*(IABS(ISYM(1))-1) 1252
C 1253
IF (EMF.NE.1.) GO TO 50 1254
BD(KP2, J)=BD(KP1, J)+(BD(KP1, J)-BD(KMAX, J))*(IABS(ISYM(3))-1) 1255
BR(KP2, J)=BR(KP1, J)+(BR(KP1, J)-BR(KMAX, J))*(IABS(ISYM(3))-1) 1256
BZ(KP2, J)=BZ(KP1, J)+(BZ(KP1, J)-BZ(KMAX, J))*(IABS(ISYM(3))-1) 1257
50 CONTINUE 1258
C ***** 1259
C 1260
60 IF (ISYM(4).EQ.0) GO TO 80 1261
IP=ISYM(4)/IABS(ISYM(4)) 1262
DO 70 K=1, KP2 1263
RHO(K, JP2)=RHO(K, JP1)+(RHO(K, JP1)-RHO(K, JMAX))*(IABS(ISYM(4))-1) 1264
U(K, JP2)=U(K, JP1)*IP+(U(K, JP1)-U(K, JMAX))*(IABS(ISYM(4))-1) 1265
V(K, JP2)=V(K, JP1)+(V(K, JP1)-V(K, JMAX))*(IABS(ISYM(4))-1) 1266
E(K, JP2)=E(K, JP1)+(E(K, JP1)-E(K, JMAX))*(IABS(ISYM(4))-1) 1267
E(K, JP2)=E(K, JP2)-(U(K, JP1)**2+V(K, JP1)**2)/2. +(U(K, JP2)**2+V(K, JP 1268
12)**2)/2. -(U(K, JP1)**2+V(K, JP1)**2)/2. -(U(K, JMAX)**2+V(K, JMAX)**2) 1269
2)/2.)*(IABS(ISYM(1))-1) 1270
C 1271
IF (EMF.NE.1.) GO TO 70 1272
BD(K, JP2)=BD(K, JP1)+(BD(K, JP1)-BD(K, JMAX))*(IABS(ISYM(4))-1) 1273
BR(K, JP2)=BR(K, JP1)+(BR(K, JP1)-BR(K, JMAX))*(IABS(ISYM(4))-1) 1274
BZ(K, JP2)=BZ(K, JP1)+(BZ(K, JP1)-BZ(K, JMAX))*(IABS(ISYM(4))-1) 1275
70 CONTINUE 1276
80 CONTINUE 1277
C 1278
C OBLIQUE BOUNDARY CONDITIONS 1279

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C		1280
	IF (IOBQ.EQ.0) GO TO 180	1281
	JBDRL=1	1282
	JBDRH=JP2	1283
	ND=ND+1	1284
	KT=0	1285
	DO 170 J=JBDRL,JBDRH	1286
	IK=IABS(IOBQ)	1287
	IF (Z(J).LT.XD(1).OR.Z(J).GT.XD(IK)) GO TO 170	1288
	DO 160 MIT=1,NVECT	1289
	IW=0	1290
	KM1=KP2/2	1291
	KM2=KM1+1	1292
	IF (NVECT.EQ.1) KM1=KP2	1293
	DO 150 N=1,KM1	1294
	IF (MIT.EQ.1) K=N+KM1	1295
	IF (MIT.EQ.2) K=KM2-N	1296
	IF (NVECT.EQ.1) K=N	1297
	I=K-1	1298
	IF (ND-1) 90,90,100	1299
	90 CALL DBLQUE (J,RDIST,DELTA)	1300
C	*****	1301
C	RDIST SHOULD BE DOUBLE PRECISION ON IBM MACHINES	1302
C	*****	1303
	RR=R(K)	1304
	IF (RDIST-RR) 110,110,140	1305
100	IF (MIT.EQ.1.AND.K.GE.IOBL(J)) GO TO 110	1306
	ID=KP2+1-IOBL(J)	1307
	IF (MIT.EQ.2.AND.K.LE.ID) GO TO 110	1308
	GO TO 140	1309
110	IW=IW+1	1310
	IF (IW.GT.1) GO TO 130	1311
	IF (ND.GT.1.AND.MIT.EQ.1) DELTA=DANGLE(J)	1312
	IF (ND.GT.1.AND.MIT.EQ.2) DELTA=-DANGLE(J)	1313
	DELTX=DELTA	1314
	L=1	1315
	IF (MIT.EQ.2) L=-1	1316
	THETA=0.	1317
	NN=K-L	1318
C	*****	1319
C	***** SETTING V*N CONDITIONS *****	1320
C	*****	1321
	IF (V(NN,J).NE.0.) THETA=V(NN,J)/ABS(V(NN,J))*2.*3.1416/360.*90.	1322
	IF (U(NN,J).NE.0.) THETA=ATAN(V(NN,J)/U(NN,J))	1323
	IF (THETA.GT.0..AND.U(NN,J).LT.0.) THETA=THETA+3.1416	1324
	IF (THETA.LT.0..AND.U(NN,J).LT.0.) THETA=THETA+3.1416	1325
	VC=(U(K-L,J)**2+V(K-L,J)**2)**0.5	1326
	VX=IOBQ/IABS(IOBQ)*COS(THETA+DELTX)*VC	1327
	VY=-SIN(THETA+DELTX)*VC	1328
	U(K,J)=VY*SIN(DELTX)+VX*COS(DELTX)	1329
	V(K,J)=VY*COS(DELTX)-VX*SIN(DELTX)	1330
	RHO(K,J)=RHO(K-L,J)	1331
	E(K,J)=E(K-L,J)	1332
	IF (EMF.NE.1.) GO TO 120	1333
	BD(K,J)=BD(K-L,J)	1334
	BR(K,J)=BR(K-L,J)	1335
	BZ(K,J)=BZ(K-L,J)	1336
120	CONTINUE	1337
	IF (ND.EQ.2.AND.IPOT.NE.0) CALL PLATE (J,MIT)	1338
	IF (ND.GT.1) GO TO 140	1339
	JLEFT=JBDRL+1	1340
	JRIGHT=JBDRH-1	1341
	IOBK(J)=K+1	1342
	IOBL(J)=K	1343


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2J)))/(3.*(1.-BETA(K,J,0,0)*DR(K)/DZ(J))) 1472
IF (1.EQ.12.AND.INSJ(J).GT.0.AND.BET.GT.2.5) PHI(K,J)=(-BETA(K,J,0 1473
1,0)*DR(K)/DZ(J))*(-4.*PHI(K,J+1)+PHI(K,J+2))+4.*PHI(K-1,J)-PHI(K-2, 1474
2J)))/(3.*(1.+BETA(K,J,0,0)*DR(K)/DZ(J))) 1475
IF (1.EQ.11.AND.INSJ(J).EQ.-1.AND.INSLND.EQ.0) PHI(K,J)=0. 1476
IF (1.EQ.11.AND.INSJ(J).EQ.-1.AND.INSLND.NE.0) PHI(K,J)=ANODE(INSL 1477
IND) 1478
IF (1.EQ.12.AND.INSJ(J).EQ.-1.AND.INSLND.EQ.0) PHI(K,J)=0. 1479
IF (1.EQ.12.AND.INSJ(J).EQ.-1.AND.INSLND.NE.0) PHI(K,J)=CATHOD(INS 1480
LND) 1481
IF (J.EQ.JP1) PHI(I,JP2)=PHI(I-1,JP1) 1482
IF (1.EQ.11) PHI(I-2,J)=2.*PHI(I-1,J)-PHI(I,J) 1483
IF (1.EQ.12) PHI(I+2,J)=2.*PHI(I+1,J)-PHI(I,J) 1484
RETURN 1485
C 1486
END 1487
SUBROUTINE SPEC 1488
C 1489
C 1490
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 1491
C ASSIGNS SPECIAL PARAMETER VALUES EVERY CYCLE 1492
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 1493
C 1494
C 1495
COMMON /CARRAY/ RHD(45,225),U(45,225),V(45,225),E(45,225),PHI(45, 1496
1225),BD(1,1),BR(1,1),BZ(1,1),DE(1,1) 1497
COMMON /CMESH/ KMAX,JMAX,KP1,JP1,KP2,JP2 1498
COMMON /CBOUND/ DANGLE(225),IOBK(225),IOBL(225),ISYM(4),IAXI,IOBQ 1499
COMMON /GRAVITY/ GC,GR,GZ 1500
COMMON /CTIME/ TIME,DT,DTT,STAB,MINDT,MAXDT,NCYCLE,NMAX 1501
COMMON /CGRID/R(45),RD(45),Z(225),DR(45),DZ(225),XD(45),ZMIN,RMIN,D 1502
IZO,DRO,IGRAPH(225),NBOUND 1503
COMMON /CCALC/ BL,EMF,MCALC,NMAGN,NTHRM,IPDT,IDFN,IPTSF 1504
COMMON /CINIT/ RHOD,VZ,VR,BO,BRO,BZO,EO,PHIO,PERMO,VELOC,ARFV,PERM 1505
1,NVECT,NPDIM 1506
COMMON/CMHD/INSJ(225),DVOLT,BASEP,DPOT,SPACE,SPINSL,JPLMIN,JPLMAX 1507
COMMON/CMATRX/ ACDEF(225),BCDEF(225),CCDEF(225),DCDEF(225),SUB(225 1508
1),DIAG(225),SUP(225),CONST(225) 1509
COMMON/ETRODE/ANODE(225),CATHOD(225) 1510
REAL*8 R,RD 1511
DATA IKT/0/ 1512
C 1513
C 1514
C IKT=IKT+1 1515
IF (IKT.GT.1) GO TO 20 1516
DO 10 J=1,JP2 1517
ANODE(J)=0. 1518
10 CATHOD(J)=0. 1519
20 CONTINUE 1520
RETURN 1521
END 1522
SUBROUTINE TMESTP 1523
C 1524
C 1525
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 1526
C COMPUTES TIME INTERVAL BETWEEN CYCLES BASED ON STABILITY CRITERIA 1527
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 1528
C 1529
C 1530
COMMON /CARRAY/ RHD(45,225),U(45,225),V(45,225),E(45,225),PHI(45, 1531
1225),BD(1,1),BR(1,1),BZ(1,1),DE(1,1) 1532
COMMON /CMESH/ KMAX,JMAX,KP1,JP1,KP2,JP2 1533
COMMON /CBOUND/ DANGLE(225),IOBK(225),IOBL(225),ISYM(4),IAXI,IOBQ 1534
COMMON /GRAVITY/ GC,GR,GZ 1535

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COMMON /CTIME/ TIME,DT,DTT,STAB,MINDT,MAXDT,NCYCLE,NMAX          1536
COMMON/CGRID/R(45),RD(45),Z(225),DR(45),DZ(225),XD(45),ZMIN,RMIN,D 1537
IZO,DRO,IGRAPH(225),NBOUND                                       1538
COMMON/CSTRSS/TRRA(225),TZZA(225),TODA(225),TRZA(225),VISC,VISCO 1539
COMMON /CCALC/ BL,EMF,MCALC,NMAGN,NTHRM,IPOT,IDFN,IPTSF         1540
COMMON /CINIT/ RHO0,VZ,VR,BO,BRO,BZO,EO,PHIO,PERM0,VELOC,ARFV,PERM 1541
1,NVECT,NPDIM                                                    1542
COMMON/CMHD/INSJ(225),DVOLT,BASEP,DPOT,SPACE,SPINSL,JPLMIN,JPLMAX 1543
COMMON /COUTP/ TITLE(15),KPDEL,JPDEL,NPLOT,NPRN,NDIGPL,NGRAPH    1544
COMMON/CMATRX/ ACDEF(225),BCDEF(225),CCDEF(225),DCDEF(225),SUB(225 1545
1),DIAG(225),SUP(225),CONST(225)                                 1546
REAL*8 R,RD                                                       1547
REAL INT,MINDT,MAXDT                                             1548
DATA DTMIN,DTHRM,DMAGN,DCONVM,DVISCN,DVISCZ,DVISCN,DHTZ,DHTR,DCONV 1549
1R,DCONVZ/11*1.E6/                                              1550
DATA DTZ,DTR,DMGZ,DMGR/4*1.E6/                                   1551
DATA BT/O./                                                       1552
C                                                                    1553
C                                                                    1554
GAMMA=GAMM(1,1)                                                  1555
STABMG=0.4                                                        1556
DO 10 J=2,JP1                                                    1557
DO 10 K=2,KP1                                                    1558
INT=E(K,J)-0.5*(U(K,J)**2+V(K,J)**2)                             1559
IF (EMF.EQ.1.) BT=(BO(K,J)**2+BR(K,J)**2+BZ(K,J)**2)/STABMG    1560
VISC=VISC(K,J,0,0)                                              1561
P=(GAMMA-1.)*RHO(K,J)*INT                                       1562
C                                                                    1563
IF (P.NE.0.OR.BT.NE.0.) DTZ=DZ(J)/(SQRT(BT/(RHO(K,J)*PERM)+ABS(GAM 1564
1MA*P/RHO(K,J))))                                               1565
US=ABS(U(K,J))                                                    1566
IF (US.GT.0.00001) DCONVZ=DZ(J)/ABS(U(K,J))                    1567
CND=COND(K,J,0,0)                                                1568
IF (CND.NE.0.) DHTZ=DZ(J)**2*RHO(K,J)*CV(K,J,0,0)/(2.*CND)     1569
DMGZ=DZ(J)**2*PERM*SIG(K,J,0,0)/2.                               1570
IF (VISC.NE.0.) DVISCZ=0.5*RHO(K,J)*DZ(J)**2/VISC              1571
C                                                                    1572
IF (P.NE.0.OR.BT.NE.0.) DTR=DR(K)/(SQRT(BT/(RHO(K,J)*PERM)+ABS(GAM 1573
1MA*P/RHO(K,J))))                                               1574
VS=ABS(V(K,J))                                                    1575
IF (VS.GT.0.00001) DCONVR=DR(K)/ABS(V(K,J))                    1576
IF (CND.NE.0.) DHTR=DR(K)**2*RHO(K,J)*CV(K,J,0,0)/(2.*CND)     1577
DMGR=DR(K)**2*PERM*SIG(K,J,0,0)/2.                               1578
IF (VISC.NE.0.) DVISCR=0.5*RHO(K,J)*DR(K)**2/VISC              1579
C                                                                    1580
C                                                                    1581
ELECTRIC FIELD          DTEF =RHO(I,J)/(SIG*B(I,J)**2)          1581
IF (DTZ.LT.DTMIN) DTMIN=DTZ                                      1582
IF (DTR.LT.DTMIN) DTMIN=DTR                                      1583
IF (DCONVZ.LT.DCONVM) DCONVM=DCONVZ                             1584
IF (DCONVR.LT.DCONVM) DCONVM=DCONVR                             1585
IF (DHTZ.LT.DTHRM) DTHRM=DHTZ                                    1586
IF (DHTR.LT.DTHRM) DTHRM=DHTR                                    1587
IF (DMGZ.LT.DMAGN) DMAGN=DMGZ                                    1588
IF (DMGR.LT.DMAGN) DMAGN=DMGR                                    1589
IF (DVISCZ.LT.DVISCN) DVISCN=DVISCZ                             1590
IF (DVISCR.LT.DVISCN) DVISCN=DVISCR                             1591
IF (DCONVM.LT.DTMIN) DTMIN=DCONVM                               1592
C                                                                    1593
10 CONTINUE                                                       1594
DT=DTMIN*STAB                                                    1595
DMAGN=DMAGN*STABMG                                              1596
DTHRM=DTHRM*STAB                                                1597
IF (DT.LT.MINDT) DT=MINDT                                       1598
IF (DT.GT.MAXDT) DT=MAXDT                                       1599

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NCONV=DCONVM/DT 1600
NVISC=DVISC/DT 1601
IF (MOD(NCYCLE,NPRN).EQ.0) WRITE (6,20) DT,DCONVM,DTHRM,DMAGN,DVIS 1602
1CM,NCONV,NTHRM,NMAGN,NVISC 1603
RETURN 1604
C 1605
C 1606
C 1607
20 FORMAT (2X,15HTIME STEP (SEC),2X,12H HYDRD ,2X,12H CONVECTION 1608
1 ,2X,12HTHERMAL COND,2X,12H MAGN DFSN ,2X,12HVISCIDUS DFSN,7H NCD 1609
2NV,9H NTHRM,9H NMAGN,9H NVISC,/,19X,5(E12.5,2X),4(I8,1X) 1610
3,/) 1611
END 1612
SUBROUTINE HULLP1 1613
C 1614
C 1615
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 1616
LAGRANGIAN REFERENCE FRAME - CALCULATION OF U, V AND E AT TIME(N+1) 1617
BASED ON VALUES OF RHO, U, V, E, PHI AND BO, BR, BZ (OR B) AT 1618
TIME (N+1) 1619
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 1620
C 1621
COMMON /CARRAY/ RHO(45,225),U(45,225),V(45,225),E(45,225),PHI(45, 1623
1225),BO(1,1),BR(1,1),BZ(1,1),DE(1,1) 1624
COMMON /CMESH/ KMAX,JMAX,KP1,JP1,KP2,JP2 1625
COMMON /CBOUND/ DANGLE(225),IOBK(225),IOBL(225),ISYM(4),IAXI,IOBQ 1626
COMMON /GRAVITY/ GC,GR,GZ 1627
COMMON /CTIME/ TIME,DT,DTT,STAB,MINDT,MAXDT,NCYCLE,NMAX 1628
COMMON/CGRID/R(45),RD(45),Z(225),DR(45),DZ(225),XD(45),ZMIN,RMIN,D 1629
1ZO,DRO,IGRAPH(225),NBOUND 1630
COMMON /CCALC/ BL,EMF,MCALC,NMAGN,NTHRM,IPDT,IDFN,IPTSF 1631
COMMON /CINIT/ RHO0,VZ,VR,BO,BRO,BZO,E0,PHI0,PERMO,VELOC,ARFV,PERM 1632
1,NVECT,NPDIM 1633
COMMON/CMHD/INSJ(225),DVOLT,BASEP,DPDT,SPACE,SPINSL,JPLMIN,JPLMAX 1634
COMMON/CMATRX/ ACDEF(225),BCDEF(225),CCDEF(225),DCDEF(225),SUB(225 1635
1),DIAG(225),SUP(225),CONST(225) 1636
COMMON/CSTORE/RHOF(2,225),UF(2,225),VF(2,225),EF(2,225),MFA(225), 1637
1UA(225),VA(225),UFA(225),VFA(225),EFA(225),PA(225) 1638
COMMON/CSTRSS/TRRA(225),TZZA(225),TDDA(225),TRZA(225),VISC,VISCO 1639
COMMON /CMAGN/BFA(225),BZZA(225),BZFA(225),BF(2,225),BFR(2,225), 1640
1BFZ(2,225) 1641
REAL*8 R,RD,RDIFF,RIPH,RIMH,RIP3H 1642
REAL JRIPH,JZIPH,JRJPH,JZJPH,JR1,JZ1,JR2,JZ2,JR,JZ 1643
REAL MU,LAM,MFA,MIP1,MJP1,M 1644
DATA THRM,DEVU,DEVV,DEVE,IL/O.,O.,O.,O.,O./ 1645
C 1646
C 1647
***** 1648
*** BL=0. (INVISCID); BL=1. (LAMINAR); BL=2. (TURBULENT) *** 1649
*** EMF=0. (NO EMF); EMF=1. (MAGN INDC); EMF=2. (LORENTZ) *** 1650
***** 1651
C 1652
C 1653
***** 1654
***** PHASE ONE ***** 1655
***** 1656
IL=IL+1 1657
GAMMA=GAMM(1,1) 1658
ILAM=0 1659
PI=3.1416 1660
IPSD=1 1661
DO 130 I=1,KP1 1662
IPSD=-IPSD 1663

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IPS=2 1664
IPF=1 1665
IF (IPSO.LT.0) IPS=1 1666
IF (IPSO.LT.0) IPF=2 1667
DO 130 J=1,JP1 1668
PM=PERM 1669
RIPH=R(I)+DR(I)/2. 1670
IF (I.EQ.1) RIMH=R(I)-DR(I)/2. 1671
IF (I.GT.1) RIMH=R(I-1)+DR(I)/2. 1672
RIP3H=R(I+1)+DR(I+1)/2. 1673
RDIFF=RIPH**2-RIMH**2 1674
C ***** 1675
C ***** COMPUTING MASS AND DENSITY AT TIME(N) ***** 1676
C ***** 1677
M=RHO(I,J)*PI*(RIPH**2-RIMH**2)*DZ(J) 1678
MIP1=RHO(I+1,J)*PI*(RIP3H**2-RIPH**2)*DZ(J) 1679
MJP1=RHO(I,J+1)*PI*(RIPH**2-RIMH**2)*DZ(J+1) 1680
RHOIPH=(M+MIP1)/(PI*(RIP3H**2-RIMH**2)*DZ(J)) 1681
RHOJPH=(M+MJP1)/(PI*(RIPH**2-RIMH**2)*(DZ(J)+DZ(J+1))) 1682
C ***** 1683
C ***** COMPUTING DENSITY AND PRESSURE AT CELL INTERFACE ***** 1684
C ***** AT TIME(N+1/2) ***** 1685
C ***** 1686
RHOIPH=RHOIPH*(1.-DT/(2.*RIPH))*(R(I+1)*V(I+1,J)-R(I)*V(I,J))/(R(I+1)-R(I)) 1687
RHOJPH=RHOJPH*(1.-DT/2.*(U(I,J+1)-U(I,J))/(Z(J+1)-Z(J))) 1688
P=(GAMMA-1.)*RHO(I,J)*(E(I,J)-0.5*(U(I,J)**2+V(I,J)**2)) 1689
PIP1=(GAMMA-1.)*RHO(I+1,J)*(E(I+1,J)-0.5*(U(I+1,J)**2+V(I+1,J)**2)) 1691
PJP1=(GAMMA-1.)*RHO(I,J+1)*(E(I,J+1)-0.5*(U(I,J+1)**2+V(I,J+1)**2)) 1693
IF (EMF.NE.1.) GO TO 10 1695
C ***** 1696
C ***** MAGNETIC PRESSURE ***** 1697
C ***** 1698
BP=BO(I,J)**2+BR(I,J)**2+BZ(I,J)**2 1699
BP1P1=BO(I+1,J)**2+BR(I+1,J)**2+BZ(I+1,J)**2 1700
BPJP1=BO(I,J+1)**2+BR(I,J+1)**2+BZ(I,J+1)**2 1701
P=P+BP/(2.*PERM) 1702
PIP1=PIP1+BP1P1/(2.*PERM) 1703
PJP1=PJP1+BPJP1/(2.*PERM) 1704
C ***** 1705
C ***** CALCULATION OF VELOCITIES AT CELL INTERFACE AT TIME(N+1/2) ***** 1706
C ***** BASED ON PRESSURE, GRAVITY AND LORENTZ FORCE ***** 1707
C ***** 1708
10 UJPH=(U(I,J)+U(I,J+1))/2.-DT/(2.*RHOJPH)*(PJP1-P)/(Z(J+1)-Z(J))-GZ 1709
1*DT/2. 1710
UIPH=(U(I,J)+U(I+1,J))/2. 1711
VI PH=(V(I+1,J)+V(I,J))/2.-DT/(2.*RHOIPH)*(PIP1-P)/(R(I+1)-R(I))-GR 1712
1*DT/2. 1713
VJPH=(V(I,J)+V(I,J+1))/2. 1714
PIPH=(PIP1+P)/2.*(1.-DT*GAMMA*(R(I+1)*V(I+1,J)-R(I)*V(I,J)))/(2.*RI 1715
1PH*(R(I+1)-R(I))) 1716
PJPH=(PJP1+P)/2.*(1.-DT*GAMMA*(U(I,J+1)-U(I,J)))/(2.*(Z(J+1)-Z(J))) 1717
1) 1718
IF (EMF.NE.2.) GO TO 20 1719
C ***** 1720
C ***** CALCULATION OF ELECTRIC CURRENTS AT CELL INTERFACE ***** 1721
C ***** AT TIME(N) ***** 1722
C ***** 1723
IPTSF=1, PHI = CURRENT STREAM FUNCTION; =2, PHI = POTENTIAL 1724
IPOT =1, ELECTRICAL TERMS ON; =2, ELECTRICAL TERMS OFF 1725
C ***** 1726
IF (I.EQ.1.OR.J.EQ.1.OR.I.EQ.KP2.OR.J.EQ.JP2) GO TO 20 1727

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CALL CURRNT (JZIPH, JR, EZ, ER, UIPH, VIPH, I, J, 1, 0) 1728
CALL CURRNT (JZ, JRIPH, EZ, ER, UIPH, VIPH, I, J, 1, 0) 1729
CALL CURRNT (JZJPH, JR, EZ, ER, UJPH, VJPH, I, J, 0, 1) 1730
CALL CURRNT (JZ, JRJPH, EZ, ER, UJPH, VJPH, I, J, 0, 1) 1731
UJPH=UJPH+DT/(2.*RHOJPH)*JRJPH*(B(I, J)+B(I, J+1))/2. 1732
VIPH=VIPH+DT/(2.*RHOIPH)*(-JZIPH*(B(I, J)+B(I+1, J))/2.) 1733
PIPH=PIPH+DT*(GAMMA-1.)*(JRIPH**2+JZIPH**2)/(2.*SIG(I, J, 1, 0, 0)) 1734
PJPH=PJPH+DT*(GAMMA-1.)*(JRJPH**2+JZJPH**2)/(2.*SIG(I, J, 0, 1, 0)) 1735
20 CONTINUE 1736
C ***** 1737
C ***** ARTIFICIAL VISCOSITY (IF NECESSARY) ***** 1738
C ***** 1739
DV=V(I+1, J)-V(I, J) 1740
DU=U(I, J+1)-U(I, J) 1741
IF (DV.LT.0.) PIPH=PIPH-DV*ARFV*(GAMMA*PIPH/RHOIPH)**0.5 1742
IF (DU.LT.0.) PJPH=PJPH-ARFV*DU*(GAMMA*PJPH/RHOJPH)**0.5 1743
C ***** 1744
C ***** CALCULATION OF MAGNETO STRESS TENSOR AT TIME(N) ***** 1745
C ***** 1746
IF (EMF.NE.1.) GO TO 30 1747
BZP1=(BZ(I+1, J)+BZ(I, J+1)+2.*BZ(I+1, J+1))/4. 1748
IF (BL.EQ.1.) ILAM=1 1749
BRP1=(BR(I+1, J)+BR(I, J+1)+2.*BR(I+1, J+1))/4. 1750
TRRIP1=-BR(I+1, J)**2/PERM 1751
TDDIP1=-BD(I+1, J)**2/PERM 1752
TRZP1=-BRP1*BZP1/PERM 1753
TZZJP1=-BZ(I, J+1)**2/PERM 1754
BRPH=(BR(I+1, J+1)+BR(I+1, J)+BR(I, J+1)+BR(I, J))/4. 1755
BZPH=(BZ(I+1, J+1)+BZ(I+1, J)+BZ(I, J+1)+BZ(I, J))/4. 1756
TRZP2=-BRP1*BZP1 1757
TRR=-BR(I, J)**2/PERM 1758
TDD=-BD(I, J)**2/PERM 1759
TRZ1=-BR(I, J)*BZ(I, J)/PERM 1760
TRZ2=-BR(I, J)*BZ(I, J)/PERM 1761
TZZ=-BZ(I, J)**2/PERM 1762
C ***** 1763
C ***** CORRECTION TO PRESSURE DUE TO MAGNETO-STRESS AT ***** 1764
C ***** CELL INTERFACE AT TIME(N+1/2) ***** 1765
C ***** 1766
DEVP1=(R(I+1)*TRRIP1*V(I+1, J)-R(I)*TRR*V(I, J))/(RIPH*(R(I+1)-R(I))) 1767
I)+(R(I+1)*U(I+1, J)*TRZP1-R(I)*U(I, J)*TRZ1)/(RIPH*(R(I+1)-R(I))) 1768
DEVP2=(TZZJP1*U(I, J+1)-TZZ*U(I, J))/(Z(J+1)-Z(J))+(TRZP2*V(I, J+1)-T 1769
IRZ2*V(I, J))/(Z(J+1)-Z(J)) 1770
PIPH=PIPH-(GAMMA-1.)*DT/(2.*RHOIPH)*DEVP1 1771
PJPH=PJPH-(GAMMA-1.)*DT/(2.*RHOJPH)*DEVP2 1772
C ***** 1773
C ***** CORRECTION OF VELOCITIES AT CELL INTERFACE AT ***** 1774
C ***** TIME(N+1/2) DUE TO MAGNETO-STRESS ***** 1775
C ***** 1776
UJPH=UJPH-DT/(2.*RHOJPH)*(TZZJP1-TZZ)/DZ(J+1) 1777
VIPH=VIPH-DT/(2.*RHOIPH)*((R(I+1)*TRRIP1-R(I)*TRR)/(RIPH*DR(I+1))- 1778
I(TDDIP1+TDD)/2./RIPH) 1779
UIPH=UIPH-DT/(2.*RHOIPH)*(R(I+1)*TRZP1-R(I)*TRZ1)/(RIPH*DR(I+1)) 1780
VJPH=VJPH-DT/(2.*RHOJPH)*(TRZP2-TRZ2)/DZ(J+1) 1781
C ***** 1782
C ***** CALCULATION OF LAMINAR STRESS COMPONENTS AT CELL ***** 1783
C ***** INTERFACE AT TIME(N+1/2) ***** 1784
C ***** 1785
30 IF (BL.NE.1.) GO TO 40 1786
ERRIPH=(V(I+1, J)-V(I, J))/(R(I+1)-R(I)) 1787
EQDIPH=VIPH/RIPH 1788
ERZPH=(U(I+1, J)-U(I, J))/(R(I+1)-R(I)) 1789
EZZJPH=(U(I, J+1)-U(I, J))/(Z(J+1)-Z(J)) 1790
ERZPH2=(V(I, J+1)-V(I, J))/(Z(J+1)-Z(J)) 1791

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EEIJPH=EZZJPH+ERRIPH+EODIPH          1792
MU=VIS(I,J,1,0)                       1793
LAM=-2./3.*MU                          1794
TRRIPH=-2.*MU*ERRIPH+LAM*EEIJPH       1795
TODIPH=-2.*MU*EODIPH+LAM*EEIJPH       1796
TRZPH=-MU*ERZPH                        1797
MU=VIS(I,J,0,1)                       1798
LAM=-2./3.*MU                          1799
TZZJPH=-2.*MU*EZZJPH+LAM*EEIJPH      1800
TRZPH2=-MU*ERZPH2                     1801
C *****                                     1802
C ***** CALCULATION OF MAGNETO STRESS COMPONENTS AT CELL ***** 1803
C ***** INTERFACE AT TIME(N+1/2) ***** 1804
C *****                                     1805
40 IF (EMF.NE.1.) GO TO 50              1806
TRRIPH=-((BR(I+1,J)+BR(I,J))/2.)*2/PERM+ILAM*TRRIPH 1807
TODIPH=-((BD(I+1,J)+BD(I,J))/2.)*2/PERM+ILAM*TODIPH 1808
TZZJPH=-((BZ(I,J+1)+BZ(I,J))/2.)*2/PERM+ILAM*TZZJPH 1809
TRZPH=-BRPH*BZPH/PERM+ILAM*TRZPH      1810
TRZPH2=-BRPH*BZPH/PERM+ILAM*TRZPH2    1811
50 IF (BL.NE.2.) GO TO 60              1812
C *****                                     1813
C ***** CALCULATION OF TURBULENT SHEAR AT CELL INTERFACE ***** 1814
C ***** AT TIME(N+1/2) ***** 1815
C *****                                     1816
ERZPH=(U(I+1,J)-U(I,J))/(R(I+1)-R(I)) 1817
MU=VIS(I,J,1,0)                       1818
TRZPH=-((MU+EDDY(I,J))*ERZPH)         1819
C *****                                     1820
60 IF (I.EQ.1.OR.J.EQ.1) GO TO 90      1821
PIMH=PA(J)                             1822
UIMH=UA(J)                             1823
VIMH=VA(J)                             1824
C *****                                     1825
C ***** PRESSURE INFLUENCE ON U,V AND E AT CELL CENTERS ***** 1826
C ***** AT TIME(N+1) ***** 1827
C *****                                     1828
SPHU=-DT*(PJPB-PJMH)/(RHO(I,J)*DZ(J))-DT*GZ 1829
SPHV=-DT*(PIPB-PIMH)/(RHO(I,J)*DR(I))-DT*GR 1830
CMPR=-DT/RHO(I,J)*((RIPH*PIPB-VIPH-RIMH*PIMH*VIMH)/(R(I)*DR(I))+ 1831
1JPH*UJPH-PJMH*UJMH)/DZ(J))          1832
IF (EMF.NE.1..AND.BL.NE.1.) GO TO 70  1833
C *****                                     1834
C ***** LAMINAR AND/OR MAGNETIC INFLUENCE ON U,V AND E ***** 1835
C ***** AT CELL CENTERS AT TIME(N+1) ***** 1836
C *****                                     1837
TRRIMH=TRRA(J)                         1838
TODIMH=TODA(J)                         1839
DEVU=-DT*((RIPH*TRZPH-RIMH*TRZA(J))/(R(I)*DR(I))+ 1840
1Z(J))/RHO(I,J)                       1841
DEVV=-DT*((RIPH*TRRIPH-RIMH*TRRIMH)/(R(I)*DR(I))+ 1842
1Z(J)-(TODIPH+TODIMH)/(RIPH+RIMH))/RHO(I,J) 1843
DEVE=-DT/RHO(I,J)*((RIPH*TRRIPH*VIPB-RIMH*TRRIMH*VIMH)/(R(I)*DR(I) 1844
1)+(RIPH*TRZPH*UIPB-RIMH*TRZA(J)*UIMH)/(R(I)*DR(I))+ 1845
1ZJMH*UJMH)/DZ(J)+(TRZPH*VJPH-TRZMH*VJMH)/DZ(J)) 1846
70 IF (BL.NE.2.) GO TO 80              1847
C *****                                     1848
C ***** TURBULENT SHEAR INFLUENCE ON U,V AND E AT CELL ***** 1849
C ***** CENTERS AT TIME(N+1) ***** 1850
C *****                                     1851
DEVU=-DT*((RIPH*TRZPH-RIMH*TRZA(J))/(R(I)*DR(I)))/RHO(I,J) 1852
DEVV=0.                                1853
DEVE=-DT/RHO(I,J)*((RIPH*TRZPH*UIPB-RIMH*TRZA(J)*UIMH)/(R(I)*DR(I)) 1854
C *****                                     1855

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C      ***** STORING U, V AND E INCREMENTS AT CELL CENTERS AT ***** 1856
C      ***** TIME(N+1) ***** 1857
C      ***** 1858
80    UF(IPS, J)=SPHU+DEVU 1859
      VF(IPS, J)=SPHV+DEVV 1860
      EF(IPS, J)=CMPR-DT*(V(I, J)+VF(IPS, J))*GR-DT*(U(I, J)+UF(IPS, J))*GZ+D 1861
      1EVE 1862
      IF (EMF.NE.2) GO TO 90 1863
C      ***** 1864
C      ***** CALCULATION OF ELECTRICAL INFLUENCE ON U, V AND E AT CELL ***** 1865
C      ***** CENTERS AT TIME(N+1) ***** 1866
C      ***** 1867
      IF (I.EQ.1.OR.I.EQ.KP2.OR.J.EQ.1.OR.J.EQ.JP2) GO TO 90 1868
      UU=U(I, J) 1869
      VV=V(I, J) 1870
      CALL CURRNT (JZ1, JR1, EZ, ER, UU, VV, I, J, 0, 0) 1871
      UP=U(I, J)+U(IPS, J) 1872
      VP=V(I, J)+V(IPS, J) 1873
      CALL CURRNT (JZ2, JR2, EZ, ER, UP, VP, I, J, 0, 0) 1874
      UF(IPS, J)=UF(IPS, J)+JR1*B(I, J)*DT/RHO(I, J) 1875
      VF(IPS, J)=VF(IPS, J)+(-JZ1*B(I, J))*DT/RHO(I, J) 1876
      EF(IPS, J)=EF(IPS, J)+(JZ2*EZ+JR2*ER)*DT/RHO(I, J) 1877
C      ***** 1878
C      ***** REVERSING CELL INTERFACE VALUES - RIGHT BOUNDARY VALUE ***** 1879
C      ***** OF LEFT CELL BECOMES LEFT BOUNDARY VALUE OF RIGHT CELL ***** 1880
C      ***** 1881
90    VA(J)=VIPH 1882
      UA(J)=UIPH 1883
      PA(J)=PIPH 1884
      UJMh=UJPH 1885
      VJMh=VJPH 1886
      PJMh=PJPH 1887
      IF (EMF.NE.1..AND.BL.NE.1.) GO TO 100 1888
      TRRA(J)=TRRIPH 1889
      TODA(J)=TODIPH 1890
      TRZA(J)=TRZPH 1891
      TRZMH=TRZPH 1892
      TRZMH2=TRZPH2 1893
      TZZJMh=TZZJPH 1894
100   IF (BL.NE.2.) GO TO 110 1895
      TRZA(J)=TRZPH 1896
C      ***** 1897
C      ***** ASSIGNING VALUES OF U, V AND E AT TIME(N+1) ***** 1898
C      ***** 1899
110   IF (J.EQ.1.OR.I.LT.9) GO TO 130 1900
      JH=1 1901
      IF (I.EQ.KP1) JH=2 1902
      DO 120 JL=1, JH 1903
      N=I-2+JL 1904
      L=IPF 1905
      IF (JL.EQ.2) L=IPS 1906
      U(N, J)=U(N, J)+UF(L, J) 1907
      V(N, J)=V(N, J)+VF(L, J) 1908
      IF (ABS(U(N, J)).LT.0.00001) U(N, J)=0. 1909
      IF (ABS(V(N, J)).LT.0.00001) V(N, J)=0. 1910
      E(N, J)=E(N, J)+EF(L, J) 1911
120   CONTINUE 1912
130   CONTINUE 1913
      RETURN 1914
C      ***** 1915
      END 1916
      SUBROUTINE HULLP2 1917
C      ***** 1918
C      ***** 1919

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C      XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX      1920
C      THE TRANSPORTING OF MASS (RE-ZONING) AND COMPUTATION OF RHO AT          1921
C      TIME(N+1) BASED ON VALUES OF RHO,U,V AND E AT TIME(N+1).                1922
C      CORRECTION OF U,V AND E AT TIME(N+1) FOR THE CONVECTION                   1923
C      OF MOMENTUM AND ENERGY RESULTING FROM THE TRANSPORTING OF MASS          1924
C      BETWEEN CELLS                                                              1925
C      XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX      1926
C      1927
C      COMMON /CARRAY/ RHO(45,225),U(45,225),V(45,225),E(45,225),PHI(45,      1928
1225),BO(1,1),BR(1,1),BZ(1,1),DE(1,1)                                         1929
COMMON /CMESH/ KMAX,JMAX,KP1,JP1,KP2,JP2                                       1930
COMMON /CBOUND/ DANGLE(225),IOBK(225),IOBL(225),ISYM(4),IAXI,IOBQ           1931
COMMON /GRAVITY/ GC,GR,GZ                                                       1932
COMMON /CTIME/ TIME,DT,DTT,STAB,MINDT,MAXDT,NCYCLE,NMAX                         1933
COMMON /CGRID/R(45),RO(45),Z(225),DR(45),DZ(225),XD(45),ZMIN,RMIN,D           1934
IZO,DRO,IGRAPH(225),NBOUND                                                    1935
COMMON /CCALC/ BL,EMF,MCALC,NMAGN,NTHRM,IPDT,IDFN,IPTSF                       1936
COMMON /CINIT/ RHO0,VZ,VR,BO,BRO,BZO,EO,PHIO,PERMO,VELDC,ARFV,PERM           1937
1,NVECT,NPDIM                                                                    1938
COMMON/CMHD/INSJ(225),DVOLT,BASEP,DPOT,SPACE,SPINSL,JPLMIN,JPLMAX             1939
COMMON/CMATRX/ ACDEF(225),BCDEF(225),CCDEF(225),DCDEF(225),SUB(225           1940
1),DIAG(225),SUP(225),CONST(225)                                              1941
COMMON/CSTORE/RHOF(2,225),UF(2,225),VF(2,225),EF(2,225),MFA(225),           1942
IUA(225),VA(225),UFA(225),VFA(225),EFA(225),PA(225)                          1943
COMMON/CSTRSS/TRRA(225),TZZA(225),TDDA(225),TRZA(225),VISC,VISCO            1944
COMMON /CMAGN/BFA(225),BZZA(225),BZFA(225),BF(2,225),BFR(2,225),           1945
IBFZ(2,225)                                                                      1946
REAL*8 R,RO,RIMH,RIPH,RIPP                                                    1947
REAL M,MIJ,MFIPH,MFIMH,MFJPH,MFJMH,MFA                                         1948
1949
C      1950
C      1951
C      1952
C      ***** PHASE TWO ***** 1953
C      ***** 1954
C      ***** 1955
C      ***** CALCULATION OF MASS, MOMENTUM, ENERGY AND MAGNETIC ***** 1956
C      ***** INDUCTION FLUX ***** 1957
C      ***** 1958
PI=3.14159 1959
DO 10 J=2,JP1 1960
VIMH=(V(1,J)+V(2,J))/2. 1961
IDM=1 1962
IF (VIMH.LT.0.) IDM=2 1963
RHOIMH=RHO(IDM,J)*(1.-DT/(R(1)+DR(1)/2.))*R(2)*V(2,J)-R(1)*V(1,J) 1964
1/(R(2)-R(1))) 1965
DRR=DR(1) 1966
RIPP=R(1)+DRR/2. 1967
MFA(J)=VIMH*RHOIMH*2.*PI*(RIPP+0.5*VIMH*DT)*DZ(J)*DT 1968
UFA(J)=MFA(J)*U(IDM,J) 1969
VFA(J)=MFA(J)*V(IDM,J) 1970
EFA(J)=MFA(J)*E(IDM,J) 1971
1972
C      IF (EMF.NE.1) GO TO 10 1973
BFA(J)=VIMH/(R(2)-R(1))*B(IDM,J)*DT 1974
BRR=(BR(2,J)+BR(1,J))/2. 1975
BZZA(J)=(U(2,J)+U(1,J))/2./R(2)-R(1))*BRR*DT 1976
BZFA(J)=(V(2,J)+V(1,J))/2./R(2)-R(1))*BZ(IDM,J)*DT 1977
10 CONTINUE 1978
IPSQ=1 1979
DO 60 I=2,KP1 1980
IPSQ=-IPSQ 1981
IPS=2 1982
IPF=1 1983

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	IF (IPSD,LT.0) IPS=1	1984
	IF (IPSD,LT.0) IPF=2	1985
	DO 60 J=2,JP1	1986
	RIPH=R(I)+DR(I)/2.	1987
	RIMH=R(I-1)+DR(I)/2.	1988
	UJPH=(U(I,J)+U(I,J+1))/2.	1989
	VIPH=(V(I,J)+V(I+1,J))/2.	1990
	UIPH=(U(I,J)+U(I+1,J))/2.	1991
	VJPH=(V(I,J)+V(I,J+1))/2.	1992
	IDP=I	1993
	JDP=J	1994
	IF (UJPH,LT.0.) JDP=J+1	1995
	IF (VIPH,LT.0.) IDP=I+1	1996
C	RHOIPH=RHO(IDP,J)*(1.-DT/RIPH*(R(I+1)*V(I+1,J)-R(I)*V(I,J)))/(R(I+1)-R(I)))	1997
	RHOJPH=RHO(I,JDP)*(1.-DT*(U(I,J+1)-U(I,J))/(Z(J+1)-Z(J)))	1998
	MFJPH=UJPH*RHOJPH**2.*PI*R(I)*DR(I)*DT	1999
C	MFIPH=VIPH*RHOIPH**2.*PI*(RIPH+0.5*VIPH*DT)*DZ(J)*DT	2000
	IF (J,NE.2) GO TO 20	2001
	UJMH=(U(I,J)+U(I,J-1))/2.	2002
	JDM=1	2003
	IF (UJMH,LT.0.) JDM=2	2004
	RHOJMH=RHO(I,JDM)*(1.-DT*(U(I,J)-U(I,J-1))/(Z(J)-Z(J-1)))	2005
	MFJMH=(U(I,1)+U(I,2))/2.*RHOJMH**2.*PI*R(I)*DR(I)*DT	2006
	UFJMH=MFJMH*U(I,JDM)	2007
	VFJMH=MFJMH*V(I,JDM)	2008
	EFJMH=MFJMH*E(I,JDM)	2009
C	IF (EMF,NE.1) GO TO 30	2010
	BFJMH=UJMH/(Z(J)-Z(J-1))*BO(I,JDM)*DT	2011
	BRFJMH=UJMH/(Z(J)-Z(J-1))*BR(I,JDM)*DT	2012
	BZZ=(BZ(I,2)+BZ(I,1))/2.	2013
	BRIJMH=(V(I,2)+V(I,1))/2./(Z(2)-Z(1))*BZZ*DT	2014
20	IF (EMF,NE.1) GO TO 30	2015
	BFIPH=VIPH/(R(I+1)-R(I))*BO(IDP,J)*DT	2016
	BZZ=(BZ(I,J)+BZ(I,J+1))/2.	2017
	BRIJPH=VJPH/(Z(J+1)-Z(J))*BZZ*DT	2018
	BZFIPH=VIPH/(R(I+1)-R(I))*BZ(IDP,J)*DT	2019
	BFJPH=UJPH/(Z(J+1)-Z(J))*B(I,JDP)*DT	2020
	BRFJPH=UJPH/(Z(J+1)-Z(J))*BR(I,JDP)*DT	2021
	BRR=(BR(I,J)+BR(I+1,J))/2.	2022
	BZIJPH=UIPH/(R(I+1)-R(I))*BRR*DT	2023
30	CONTINUE	2024
C	UFIPH=MFIPH*U(IDP,J)	2025
	VFIPH=MFIPH*V(IDP,J)	2026
	UFJPH=MFJPH*U(I,JDP)	2027
	VFJPH=MFJPH*V(I,JDP)	2028
	EFIPH=MFIPH*E(IDP,J)	2029
	EFJPH=MFJPH*E(I,JDP)	2030
	MFIMH=MFA(J)	2031
	UFIMH=UFA(J)	2032
	VFIMH=VFA(J)	2033
	EFIMH=EFA(J)	2034
C		2035
C		2036
C		2037
C		2038
C		2039
C		2040
C		2041
C		2042
C		2043
C		2044
	M=RHO(I,J)*PI*(RIPH**2-RIMH**2)*DZ(J)	2045
	MIJ=RHO(I,J)*PI*(RIPH**2-RIMH**2)*DZ(J)+MFIMH+MFJMH-MFIPH-MFJPH	2046
C		2047

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RHD(IPS, J)=MIJ/(PI*(RIPH**2-RIMH**2)*DZ(J))
C
C *****
C ***** CORRECTION OF VELOCITIES AND ENERGY DUE *****
C ***** CONVECTION *****
C
UF(IPS, J)=(U(I, J)*M+UFIMH+UFJMH-UFIPH-UFJPH)/MIJ
VF(IPS, J)=(V(I, J)*M+VFIMH+VFJMH-VFIPH-VFJPH)/MIJ
INT=(E(I, J)*M+EFIMH+EFJMH-EFIPH-EFJPH-0.5*(U(I, J)**2+V(I, J)**2)*MI
I J)/MIJ
EF(IPS, J)=INT+(U(I, J)**2+V(I, J)**2)/2.
MFJMH=MFJPH
UFJMH=UFJPH
VFJMH=VFJPH
EFJMH=EFJPH
C
IF (EMF.NE.1) GO TO 40
BFIMH=BFA(J)
BZIJMH=BZZA(J)
BZFIMH=BZFA(J)
BF(IPS, J)=(BD(I, J)+BFIMH+BFJMH-BFIPH-BFJPH)
BFR(IPS, J)=(BR(I, J)-BRIJMH+BRFJMH+BRIJPH-BRFJPH)
BFZ(IPS, J)=(BZ(I, J)+BZFIMH-BZIJMH-BZFIPH+BZIJPH)
BFJMH=BFJPH
BRFJMH=BRFJPH
BRIJMH=BRIJPH
BFA(J)=BFIPH
BZZA(J)=BZIJPH
BZFA(J)=BZFIPH
C
40 MFA(J)=MFIPH
UFA(J)=UFIPH
VFA(J)=VFIPH
EFA(J)=EFIPH
C *****
C ***** ASSIGNING VALUES TO RHO, U, V, EB, BR AND BZ *****
C ***** AT TIME(N+1) *****
C *****
IF (I.LT.3) GO TO 60
JH=1
IF (I.EQ.KP1) JH=2
DO 50 JL=1, JH
N=I-2+JL
L=IPF
IF (JL.EQ.2) L=IPS
RHO(N, J)=RHD(L, J)
U(N, J)=UF(L, J)
V(N, J)=VF(L, J)
IF (ABS(U(N, J)).LT.0.00001) U(N, J)=0.
IF (ABS(V(N, J)).LT.0.00001) V(N, J)=0.
E(N, J)=EF(L, J)
C
IF (EMF.NE.1) GO TO 50
BD(N, J)=BF(L, J)
BR(N, J)=BFR(L, J)
BZ(N, J)=BFZ(L, J)
50 CONTINUE
60 CONTINUE
RETURN
END
SUBROUTINE EFIELD
C
C
C
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

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C SOLVES ELECTRIC POTENTIAL OR STREAM FUNCTION ELLIPTIC PDE 2112
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 2113
C 2114
C 2115
C DIMENSION CDEF1(45,225),CDEF2(45,225),CDEF3(45,225),CDEF4(45,225), 2116
C ICDEF5(45,225) 2117
COMMON /CARRAY/ RHO(45,225),U(45,225),V(45,225),E(45,225),PHI(45, 2118
1225),BO(1,1),BR(1,1),BZ(1,1),DE(1,1) 2119
COMMON /CMESH/ KMAX,JMAX,KP1,JP1,KP2,JP2 2120
COMMON /CBOUND/ DANGLE(225),IOBK(225),IOBL(225),ISYM(4),IAXI,IOBO 2121
COMMON /GRAVITY/ GC,GR,GZ 2122
COMMON /CTIME/ TIME,DT,DTT,STAB,MINDT,MAXDT,NCYCLE,NMAX 2123
COMMON /CGRID/R(45),RD(45),Z(225),DR(45),DZ(225),XD(45),ZMIN,RMIN,D 2124
1Z0,DRO,IGRAPH(225),NBOUND 2125
COMMON /CCALC/ BL,EMF,MCALC,NMAGN,NTHRM,IPDT,IDFN,IPTSF 2126
COMMON /CINIT/ RHDO,VZ,VR,BO,BRO,BZO,EO,PHIO,PERMO,VELDC,ARFV,PERM 2127
1,NVECT,NPDIM 2128
COMMON /CMHD/INSJ(225),DVOLT,BASEP,DPDT,SPACE,SPINSL,JPLMIN,JPLMAX 2129
COMMON /CMATRIX/ ACDEF(225),BCDEF(225),CCDEF(225),DCDEF(225),SUB(225 2130
1),DIAG(225),SUP(225),CONST(225) 2131
REAL*8 R,RD 2132
ITER=0 2133
10 CONTINUE 2134
ITER=ITER+1 2135
ID=1 2136
JD=1 2137
DIFMAX=0. 2138
C 2139
C 2140
C ***** 2141
C ***** FOR SOR, OMEGA=1.75. FOR GAUSS-SEIDEL, OMEGA=1.0. ***** 2142
C ***** 2143
C OMEGA=1.75 2144
DO 80 J=2,JP1 2145
IX=KP2-IOBL(J)+2 2146
IY=IOBL(J)-1 2147
IF(IX.LE.1.DR,IY.GE.KP2) WRITE(6,120) 2148
DO 70 I=IX,IY 2149
C IF(ITER.GT.1) GO TO 55 2150
DR2=1./((R(I)-R(I-1))*DR(I)) 2151
DR1=1./((R(I+1)-R(I))*DR(I)) 2152
DBETA=(BETA(I,J,0,1)-BETA(I,J,0,-1))/DZ(J) 2153
BBR=+DR1+DR2 2154
C ***** 2155
UIPH=(U(I,J)+U(I+1,J))/2. 2156
UJPH=(U(I,J)+U(I,J+1))/2. 2157
UJMH=(U(I,J)+U(I,J-1))/2. 2158
VJPH=(V(I,J)+V(I,J+1))/2. 2159
VJMH=(V(I,J)+V(I,J-1))/2. 2160
BJPH=(B(I,J)+B(I,J+1))/2. 2161
BJMH=(B(I,J)+B(I,J-1))/2. 2162
UIMH=(U(I,J)+U(I-1,J))/2. 2163
VIPH=(V(I,J)+V(I+1,J))/2. 2164
VIMH=(V(I,J)+V(I-1,J))/2. 2165
BIPH=(B(I,J)+B(I+1,J))/2. 2166
BIMH=(B(I,J)+B(I-1,J))/2. 2167
C 2168
IF (IPTSF.NE.2) GO TO 20 2169
DCOND1=(SIG(I,J,1,0,1)-SIG(I,J,-1,0,1))/DR(I)*SIG(I,J,0,0,1) 2170
DCOND2=(SIG(I,J,0,1,1)-SIG(I,J,0,-1,1))/DZ(J)*SIG(I,J,0,0,1) 2171
A=(DR1+1./((2.*DR(I))*DCOND1-BETA(I,J,0,0)*DCOND2-DBETA)) 2172
C=(DR2-1./((2.*DR(I))*DCOND1-BETA(I,J,0,0)*DCOND2-DBETA)) 2173
D=((U(I,J)*B(I,J)-BETA(I,J,0,0)*V(I,J)*B(I,J))*DCOND1-(UIPH*BIPH-B 2174
1ETA(I,J,1,0)*VIPH*BIPH-UIMH*BIMH+BETA(I,J,-1,0)*VIMH*BIMH)/DR(I)) 2175

```

```

      GO TO 30
C
20 DCOND1=(SIG(I,J,1,0,0)-SIG(I,J,-1,0,0))/(DR(I)*SIG(I,J,0,0,0))
   DCOND2=(SIG(I,J,1,0,1)-SIG(I,J,-1,0,1))/(DZ(J)*SIG(I,J,0,0,0))
   A=(DR1+1./(2.*DR(I))*(-DCOND1-BETA(I,J,0,0)*DCOND2+DBETA))
   C=(DR2-1./(2.*DR(I))*(-DCOND1-BETA(I,J,0,0)*DCOND2+DBETA))
   D=-SIG(I,J,0,0,0)*(BJPH*UJPH-BJMH*UJMH)/DZ(J)
C
30 DZ1=1./((Z(J+1)-Z(J))*DZ(J))
   DZ2=1./((Z(J)-Z(J-1))*DZ(J))
   DBETA=(BETA(I,J,1,0)-BETA(I,J,-1,0))/DR(I)
   BP=+DZ1+DZ2
C
   IF (IPTSF.NE.2) GO TO 40
   DCOND1=(SIG(I,J,0,1,1)-SIG(I,J,0,-1,1))/(DZ(J)*SIG(I,J,0,0,1))
   DCOND2=(SIG(I,J,1,0,1)-SIG(I,J,-1,0,1))/(DR(I)*SIG(I,J,0,0,1))
   AP=(DZ1+1./(2.*DZ(J))*(DCOND1+BETA(I,J,0,0)*DCOND2+DBETA))
   CP=(DZ2-1./(2.*DZ(J))*(DCOND1+BETA(I,J,0,0)*DCOND2+DBETA))
   DP=(-(V(I,J)*B(I,J)+BETA(I,J,0,0)*U(I,J)*B(I,J))*DCOND1+(VJPH*BJPH
1+BETA(I,J,0,1)*UJPH*BJPH-VJMH*BJMH-BETA(I,J,0,-1)*UJMH*BJMH)/DZ(J)
2)
   GO TO 50
C
40 DCOND1=(SIG(I,J,0,1,0)-SIG(I,J,0,-1,0))/(DZ(J)*SIG(I,J,0,0,0))
   DCOND2=(SIG(I,J,1,0,0)-SIG(I,J,-1,0,0))/(DR(I)*SIG(I,J,0,0,0))
   AP=(DZ1+1./(2.*DZ(J))*(DCOND1+BETA(I,J,0,0)*DCOND2-DBETA))
   CP=(DZ2-1./(2.*DZ(J))*(DCOND1+BETA(I,J,0,0)*DCOND2-DBETA))
   DP=-SIG(I,J,0,0,0)*(BIPH*VIPH-BIMH*VIMH)/DR(I)
C
50 CONTINUE
C
*****
C
COEF1,.....COEF5 ARE ARRAYS, WHICH WHEN USED, WILL REDUCE THE
CONVERGENCE TIME (CP) BY A FACTOR OF 3 OR 4 AT THE EXPENSE OF
ADDITIONAL CORE.
C
*****
C
COEF1(I,J)=(-D-DP)/(BBR+BP)
C
COEF2(I,J)=A/(BBR+BP)
C
COEF3(I,J)=AP/(BBR+BP)
C
COEF4(I,J)=C/(BBR+BP)
C
COEF5(I,J)=CP/(BBR+BP)
C
55 IF (I.EQ.1X.DR,I.EQ.1Y.DR,J.EQ.2.DR,J.EQ.JP1) CALL BNDPOT (I,J)
   OLDPHI=PHI(I,J)
   PHI(I,J)=(-D-DP+A*PHI(I+1,J)+AP*PHI(I,J+1)+C*PHI(I-1,J)+CP*PHI(I,J
1-1))/(BBR+BP)
C
   PHI(I,J)=COEF1(I,J)+COEF2(I,J)*PHI(I+1,J)+COEF3(I,J)*PHI(I,J+1)+
C
   1COEF4(I,J)*PHI(I-1,J)+COEF5(I,J)*PHI(I,J-1)
   PHI(I,J)=PHI(I,J)*OMEGA+(1.-OMEGA)*OLDPHI
   DIFF=ABS(PHI(I,J)-OLDPHI)/(5.*SIG(I,J,0,0,0)*U(I,J)*B(I,J))
   IF (DIFF.LE.DIFMAX) GO TO 60
   ID=I
   JD=J
   OLDIE=OLDPHI
   GOODIE=PHI(I,J)
   DIFMAX=DIFF
60 CONTINUE
70 CONTINUE
80 CONTINUE
C
DO 100 J=2,JP1
   I1=KP2-IOBL(J)+2
   I2=IOBL(J)-1
DO 90 I=I1,I2
   IF (I.EQ.I1.DR,I.EQ.I2.DR,J.EQ.2.DR,J.EQ.JP1) CALL BNDPOT (I,J)
90 CONTINUE

```

```

100 CONTINUE
WRITE (6,110) ID,JD,DIFMAX,ITER
IF (ITER.GT.100) RETURN
IF (DIFMAX.GT..0010) GO TO 10
RETURN
C
C
110 FORMAT (35H ELECTRICAL CONVERGENCE ...AT CELL,2(1X,13),15H DIFFE
RENCE = ,E12.4,3X,15HFOR ITERATION ,13)
120 FORMAT(85H ELECTRODES CANNOT LIE ON THE BOUNDARY.... REDUCE "RD
1 S" BY 1 OR 2 "DRO S" )
END
SUBROUTINE CURRNT (JZ, JR, EZ, ER, UU, VV, I, J, IHALF, JHALF)
C
C
C
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
COMPUTES ELECTRIC FIELD AND CURRENT BASED ON THE STREAM CURRENT
FUNCTION, POTENTIAL OR INDUCED MAGNETIC FIELD
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C
C
COMMON /CARRAY/ RHO(45,225),U(45,225),V(45,225),E(45,225),PHI(45,
1225),BO(1,1),BR(1,1),BZ(1,1),DE(1,1)
COMMON /CMESH/ KMAX, JMAX, KP1, JP1, KP2, JP2
COMMON /CBOUND/ DANGLE(225), IOBK(225), IOBL(225), ISYM(4), IAXI, IOBQ
COMMON /GRAVTY/ GC, GR, GZ
COMMON /CTIME/ TIME, DT, DTT, STAB, MINDT, MAXDT, NCYCLE, NMAX
COMMON /CGRID/ R(45), RD(45), Z(225), DR(45), DZ(225), XD(45), ZMIN, RMIN, D
120, DR0, IGRAPH(225), NBOUND
COMMON /CCALC/ BL, EMF, MCALC, NMAGN, NTHRM, IPDT, IDFN, IPTSF
COMMON /CINIT/ RH00, VZ, VR, BO, BRO, BZO, EO, PHIO, PERMO, VELDC, ARFV, PERM
1, NVECT, NPDIM
COMMON /CMHD/ INSJ(225), DVOLT, BASEP, DPOT, SPACE, SPINSL, JPLMIN, JPLMAX
COMMON /CMATRX/ ACDEF(225), BCDEF(225), CCDEF(225), DCDEF(225), SUB(225
1), DIAG(225), SUP(225), CONST(225)
REAL*8 R, RD
REAL JR, JZ
C
C
EZ=0.
ER=EZ
JZ=ER
JR=JZ
IF (1.EQ.1.DR.1.EQ.KP2.DR.J.EQ.1.DR.J.EQ.JP2) RETURN
IF (EMF.EQ.1) GO TO 20
DPHIR=((PHI(I+1,J)-PHI(I-1,J))+JHALF*(PHI(I+1,J+1)-PHI(I-1,J+1))+I
1HALF*(PHI(I-1,J)-PHI(I,J)))/(R(I+1)-R(I-1)+JHALF*(R(I-1)-R(I+1))+4.
2*DR(I))+IHALF*(R(I-1)-R(I)))
DPHIZ=((PHI(I,J+1)-PHI(I,J-1))+IHALF*(PHI(I+1,J+1)-PHI(I+1,J-1))+J
1HALF*(PHI(I,J-1)-PHI(I,J)))/(Z(J+1)-Z(J-1)+IHALF*(Z(J-1)+Z(J+1))+4.
2*DZ(J))+JHALF*(Z(J-1)-Z(J)))
IF (IPTSF.EQ.2) GO TO 10
C
C
C
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
CURRENT STREAM FUNCTION
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C
C
JZ=DPHIR
JR=-DPHIZ
GO TO 20
10 CONTINUE
C
C
C
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
POTENTIAL
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
JZ=SIG(I, J, IHALF, JHALF, 1)*((-DPHIZ+VV*(B(I+IHALF, J+JHALF)+B(I, J)))/
12.)-BETA(I, J, IHALF, JHALF)*(DPHIR-UU*(B(I+IHALF, J+JHALF)+B(I, J)))/2

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C		2368
C		2369
C	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX	2370
C	CALCULATES MAGNETIC DIFFUSION	2371
C	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX	2372
C		2373
C		2374
C	COMMON /CARRAY/ RHD(45,225),U(45,225),V(45,225),E(45,225),PHI(45,	2375
	1225),BD(1,1),BR(1,1),BZ(1,1),DE(1,1)	2376
	COMMON /CMESH/ KMAX,JMAX,KP1,JP1,KP2,JP2	2377
	COMMON /CBOUND/ DANGLE(225),IDBK(225),IDBL(225),ISYM(4),IAXI,IOBO	2378
	COMMON /GRAVITY/ GC,GR,GZ	2379
	COMMON /CTIME/ TIME,DT,DTT,STAB,MINDT,MAXDT,NCYCLE,NMAX	2380
	COMMON/CGRID/R(45),RD(45),Z(225),DR(45),DZ(225),XD(45),ZMIN,RMIN,D	2381
	IZO,DRO,IGRAPH(225),NBOUND	2382
	COMMON /CCALC/ BL,EMF,MCALC,NMAGN,NTHRM,IPDT,IDFN,IPTSF	2383
	COMMON /CINIT/ RHOO,VZ,VR,BO,BRO,BZO,EO,PHIO,PERMO,VELDC,ARFV,PERM	2384
	I,NVECT,NPDIM	2385
	COMMON/CMHD/INSJ(225),DVOLT,BASEP,DPOT,SPACE,SPINSL,JPLMIN,JPLMAX	2386
	COMMON/CMATRIX/ ACDEF(225),BCDEF(225),CCDEF(225),DCDEF(225),SUB(225	2387
	1),DIAG(225),SUP(225),CONST(225)	2388
	REAL*8 R,RD,RIPH,RIMH	2389
		2390
C		2391
C	*****	2392
C	MAGNETIC AND THERMAL TRANSPORT	2393
C	*****	2394
C	DO 100 IFIELD=1,3	2395
	DO 90 NDT=1,NMAGN	2396
	CALL BOUND	2397
	DO 30 J=2,JP1	2398
	DO 30 I=2,KP1	2399
	RIPH=(R(I)+R(I+1))/2.	2400
	RIMH=R(I-1)+DR(I)/2.	2401
	T1=DT/((R(I+1)-R(I))*DR(I)*R(I))/NMAGN	2402
	T2=DT/((R(I)-R(I-1))*DR(I)*R(I))/NMAGN	2403
	T3=DT/((Z(J+1)-Z(J))*DZ(J))/NMAGN	2404
	T4=DT/((Z(J)-Z(J-1))*DZ(J))/NMAGN	2405
	IF (IFIELD.GT.1) GO TO 10	2406
	DB1=(BD(I+1,J)/SIG(I,J,1,0,0)-BD(I,J)/SIG(I,J,1,0,0))*RIPH	2407
	DB2=(BD(I-1,J)/SIG(I,J,-1,0,0)-BD(I,J)/SIG(I,J,-1,0,0))*RIMH	2408
	DB3=BD(I,J+1)/SIG(I,J,0,1,0)-BD(I,J)/SIG(I,J,0,1,0)	2409
	DB4=BD(I,J-1)/SIG(I,J,0,-1,0)-BD(I,J)/SIG(I,J,0,-1,0)	2410
	DE(I,J)=(T1*DB1+T2*DB2+T3*DB3+T4*DB4)/PERM	2411
	10 IF (IFIELD.NE.2) GO TO 20	2412
	DBR1=(BR(I+1,J)/SIG(I,J,+1,0,0)-BR(I,J)/SIG(I,J,+1,0,0))*RIPH	2413
	DBR2=(BR(I-1,J)/SIG(I,J,-1,0,0)-BR(I,J)/SIG(I,J,-1,0,0))*RIMH	2414
	DBR3=BR(I,J+1)/SIG(I,J,0,+1,0)-BR(I,J)/SIG(I,J,0,+1,0)	2415
	DBR4=BR(I,J-1)/SIG(I,J,0,-1,0)-BR(I,J)/SIG(I,J,0,-1,0)	2416
	DE(I,J)=(T1*DBR1+T2*DBR2+T3*DBR3+T4*DBR4)/PERM	2417
	20 IF (IFIELD.NE.3) GO TO 30	2418
	DBZ1=(BZ(I+1,J)/SIG(I,J,+1,0,0)-BZ(I,J)/SIG(I,J,+1,0,0))*RIPH	2419
	DBZ2=(BZ(I-1,J)/SIG(I,J,-1,0,0)-BZ(I,J)/SIG(I,J,-1,0,0))*RIMH	2420
	DBZ3=BZ(I,J+1)/SIG(I,J,0,+1,0)-BZ(I,J)/SIG(I,J,0,+1,0)	2421
	DBZ4=BZ(I,J-1)/SIG(I,J,0,-1,0)-BZ(I,J)/SIG(I,J,0,-1,0)	2422
	DE(I,J)=(T1*DBZ1+T2*DBZ2+T3*DBZ3+T4*DBZ4)/PERM	2423
	30 CONTINUE	2424
	IF (IDFN.EQ.2) GO TO 100	2425
		2426
C	*****	2427
C	MAGNETIC DIFFUSION	2428
C	*****	2429
C	IF (IFIELD.GT.1) GO TO 50	2430
	DO 40 I=2,KP1	2431

```

DD 40 J=2,JP1                                2432
BD(I,J)=BD(I,J)+DE(I,J)                      2433
40 CONTINUE                                   2434
50 IF (FIELD.NE.2) GO TO 70                   2435
DD 60 I=2,KP1                                  2436
DD 60 J=2,JP1                                  2437
BR(I,J)=BR(I,J)+DE(I,J)                      2438
60 CONTINUE                                   2439
70 IF (FIELD.NE.3) GO TO 90                   2440
DD 80 I=2,KP1                                  2441
DD 80 J=2,JP1                                  2442
BZ(I,J)=BZ(I,J)+DE(I,J)                      2443
80 CONTINUE                                   2444
90 CONTINUE                                   2445
100 CONTINUE                                  2446
CALL SECOND (A)                               2447
C                                               2448
C IF (IDFN.EQ.1) GO TO 140                    2449
C *****                                     2450
C THERMAL CONDUCTION                          2451
C *****                                     2452
DD 130 NDT=1,NTHRM                            2453
CALL BOUND                                    2454
DD 110 I=2,KP1                                 2455
RIPH=(R(I)+R(I+1))/2.                         2456
RIMH=(R(I)+R(I-1))/2.                         2457
DD 110 J=2,JP1                                 2458
T=(E(I,J)-0.5*(U(I,J)**2+V(I,J)**2))/CV(I,J,0,0) 2459
TP1=(E(I+1,J)-0.5*(U(I+1,J)**2+V(I+1,J)**2))/CV(I+1,J,0,0) 2460
TM1=(E(I-1,J)-0.5*(U(I-1,J)**2+V(I-1,J)**2))/CV(I-1,J,0,0) 2461
TP2=(E(I,J+1)-0.5*(U(I,J+1)**2+V(I,J+1)**2))/CV(I,J+1,0,0) 2462
TM2=(E(I,J-1)-0.5*(U(I,J-1)**2+V(I,J-1)**2))/CV(I,J-1,0,0) 2463
T1=DT/((R(I+1)-R(I))*DR(I)*R(I))/NTHRM        2464
T2=DT/((R(I)-R(I-1))*DR(I)*R(I))/NTHRM        2465
T3=DT/((Z(J+1)-Z(J))*DZ(J))/NTHRM             2466
T4=DT/((Z(J)-Z(J-1))*DZ(J))/NTHRM             2467
DT1=(TP1*COND(I,J,+1,0)-T*COND(I,J,+1,0))*RIPH 2468
DT2=(TM1*COND(I,J,-1,0)-T*COND(I,J,-1,0))*RIPH 2469
DT3=TP2*COND(I,J,0,+1)-T*COND(I,J,0,+1)       2470
DT4=TM2*COND(I,J,0,-1)-T*COND(I,J,0,-1)       2471
DE(I,J)=(T1*DT1+T2*DT2+T3*DT3+T4*DT4)/RHO(I,J) 2472
110 CONTINUE                                  2473
DD 120 I=2,KP1                                 2474
DD 120 J=2,JP1                                 2475
120 E(I,J)=E(I,J)+DE(I,J)                     2476
130 CONTINUE                                  2477
140 CONTINUE                                  2478
RETURN                                         2479
END                                             2480
SUBROUTINE TEMDIF                              2481
C                                               2482
C                                               2483
C *****                                     2484
C CALCULATES THERMAL DIFFUSION IMPLICITLY     2485
C *****                                     2486
C *****                                     2487
C *****                                     2488
COMMON /CARRAY/ RHO(45,225),U(45,225),V(45,225),E(45,225),PHI(45,
1225),BD(1,1),BR(1,1),BZ(1,1),DE(1,1)        2490
COMMON /CMESH/ KMAX,JMAX,KP1,JP1,KP2,JP2      2491
COMMON /CBOUND/ DANGLE(225),IOBK(225),IOBL(225),ISYM(4),IAXI,IOBQ 2492
COMMON /GRAVITY/ GC,GR,GZ                     2493
COMMON /CTIME/ TIME,DT,DTT,STAB,MINDT,MAXDT,NCYCLE,NMAX 2494
COMMON/CGRID/R(45),RD(45),Z(225),DR(45),DZ(225),XD(45),ZMIN,RMIN,D 2495

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1ZO, DRO, IGRAPH(225), NBOUND                                2496
COMMON /CCALC/ BL, EMF, MCALC, NMAGN, NTHRM, IPOT, IDFN, IPTSF 2497
COMMON /CINIT/ RHO0, VZ, VR, BO, BRO, BZO, EO, PHIO, PERMO, VELQC, ARFV, PERM 2498
1, NVECT, NPDIM                                             2499
COMMON/CMHD/INSJ(225), DVOLT, BASEP, DPOT, SPACE, SPINSL, JPLMIN, JPLMAX 2500
COMMON/CMATRX/ ACDEF(225), BCDEF(225), CCDEF(225), DCDEF(225), SUB(225 2501
1), DIAG(225), SUP(225), CONST(225)                         2502
REAL*8 R, RD                                               2503
C                                                            2504
C                                                            2505
DO 20 J=2, JP1                                             2506
DO 10 K=2, KP1                                             2507
I=K                                                         2508
ENERGY=E(K, J)-0.5*(U(K, J)**2+V(K, J)**2)                2509
DR1=1./((R(K+1)-R(K))*DR(K))                               2510
DR2=1./((R(K)-R(K-1))*DR(K))                               2511
DCOND1=1./((COND(K, J, 0, 0)*DZ(J))*((COND(K, J, 0, 1)-COND(K, J, 0, -1))) 2512
ALPHA=RHO(K, J)*CV(K, J, 0, 0)/COND(K, J, 0, 0)           2513
ACDEF(I-1)=DR1+1./((2.*DR(K))*DCOND1)                     2514
BCDEF(I-1)=-DR1-DR2-ALPHA/DT                               2515
CCDEF(I-1)=DR2-1./((2.*DR(K))*DCOND1)                     2516
DCDEF(I-1)=-ALPHA/DT*ENERGY/CV(K, J, 0, 0)                2517
10 CONTINUE                                               2518
CALL KSWEEP (J)                                           2519
20 CONTINUE                                               2520
DO 40 K=2, KP1                                             2521
DO 30 J=2, JP1                                             2522
ENERGY=E(K, J)-0.5*(U(K, J)**2+V(K, J)**2)                2523
DZ1=1./((Z(J+1)-Z(J))*DZ(J))                               2524
DZ2=1./((Z(J)-Z(J-1))*DZ(J))                               2525
DCOND1=1./((COND(K, J, 0, 0)*DR(K))*((COND(K, J, 1, 0)-COND(K, J, -1, 0))) 2526
ALPHA=RHO(K, J)*CV(K, J, 0, 0)/COND(K, J, 0, 0)           2527
ACDEF(J-1)=DZ1+1./((2.*DZ(J))*DCOND1)                     2528
BCDEF(J-1)=-DZ1-DZ2-ALPHA/DT                               2529
CCDEF(J-1)=DZ2-1./((2.*DZ(J))*DCOND1)                     2530
DCDEF(J-1)=-ALPHA/DT*ENERGY/CV(K, J, 0, 0)                2531
30 CONTINUE                                               2532
CALL JSWEEP (K)                                           2533
40 CONTINUE                                               2534
RETURN                                                     2535
END                                                         2536
SUBROUTINE TRID (M)                                        2537
C                                                            2538
C                                                            2539
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 2540
SETS-UP TRI-DIAGONAL MATRIX FOR IMPLICIT INTEGRATION      2541
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 2542
C                                                            2543
C                                                            2544
COMMON/CMATRX/ ACDEF(225), BCDEF(225), CCDEF(225), DCDEF(225), SUB(225 2545
1), DIAG(225), SUP(225), CONST(225)                         2546
C                                                            2547
N=M                                                         2548
NN=N-1                                                      2549
SUP(1)=SUP(1)/DIAG(1)                                       2550
CONST(1)=CONST(1)/DIAG(1)                                   2551
DO 10 I=2, N                                                2552
II=I-1                                                      2553
DIAG(I)=DIAG(I)-SUP(II)*SUB(I)                              2554
IF (I.EQ.N) GO TO 10                                        2555
SUP(I)=SUP(I)/DIAG(I)                                       2556
10 CONST(I)=(CONST(I)-SUB(II)*CONST(II))/DIAG(I)           2557
DO 20 K=1, NN                                               2558
I=N-K                                                        2559

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```

CONST(I)=CONST(I)-SUP(I)*CONST(I+1)
20 CONTINUE
RETURN
END
SUBROUTINE KSWEEP (J)
C
C
C
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C
IMPLICIT SWEEP IN THE K DIRECTION
C
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C
C
COMMON /CARRAY/ RHO(45,225),U(45,225),V(45,225),E(45,225),PHI(45,
1225),BO(1,1),BR(1,1),BZ(1,1),DE(1,1)
COMMON /CMESH/ KMAX,JMAX,KP1,JP1,KP2,JP2
COMMON /CMATRIX/ ACDEF(225),BCDEF(225),CCDEF(225),DCDEF(225),SUB(225
1),DIAG(225),SUP(225),CONST(225)
COMMON /CCALC/ BL,EMF,MCALC,NMAGN,NTHRM,IPDT,IDFN,IPTSF
C
C
IF (IDFN.NE.1) GO TO 10
DCDEF(1)=DCDEF(1)-CCDEF(1)*PHI(1,J)
DCDEF(KMAX)=DCDEF(KMAX)-ACDEF(KMAX)*PHI(KP2,J)
GO TO 20
10 ENER1=E(1,J)-0.5*(U(1,J)**2+V(1,J)**2)
ENER2=E(KP2,J)-0.5*(U(KP2,J)**2+V(KP2,J)**2)
DCDEF(1)=DCDEF(1)-CCDEF(1)*ENER1/CV(1,J,0,0)
DCDEF(KMAX)=DCDEF(KMAX)-ACDEF(KMAX)*ENER2/CV(KP2,J,0,0)
20 CONTINUE
DO 30 K=1,KMAX
INDEX=KMAX-K+1
DIAG(INDEX)=BCDEF(K)
SUP(INDEX)=CCDEF(K)
SUB(INDEX)=ACDEF(K)
CONST(INDEX)=DCDEF(K)
30 CONTINUE
CALL TRID (KMAX)
DO 40 K=1,KMAX
L=KMAX-K+1
DE(K+1,J)=CONST(L)
40 CONTINUE
RETURN
C
END
SUBROUTINE JSWEEP (K)
C
C
C
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C
IMPLICIT SWEEP IN THE J DIRECTION
C
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C
C
COMMON /CARRAY/ RHO(45,225),U(45,225),V(45,225),E(45,225),PHI(45,
1225),BO(1,1),BR(1,1),BZ(1,1),DE(1,1)
COMMON /CMESH/ KMAX,JMAX,KP1,JP1,KP2,JP2
COMMON /CMATRIX/ ACDEF(225),BCDEF(225),CCDEF(225),DCDEF(225),SUB(225
1),DIAG(225),SUP(225),CONST(225)
COMMON /CCALC/ BL,EMF,MCALC,NMAGN,NTHRM,IPDT,IDFN,IPTSF
C
C
IF (IDFN.NE.1) GO TO 10
DCDEF(1)=DCDEF(1)-CCDEF(1)*PHI(K,1)
DCDEF(JMAX)=DCDEF(JMAX)-ACDEF(JMAX)*PHI(K,JP2)
GO TO 20

```

```

10 ENER1=E(K,1)-0.5*(U(K,1)**2+V(K,1)**2) 2624
   ENER2=E(K,JP2)-0.5*(U(K,JP2)**2+V(K,JP2)**2) 2625
   DCDEF(1)=DCDEF(1)-CCDEF(1)*ENER1/CV(K,1,0,0) 2626
   DCDEF(JMAX)=DCDEF(JMAX)-ACDEF(JMAX)*ENER2/CV(K,JP2,0,0) 2627
20 CONTINUE 2628
   DO 30 J=1,JMAX 2629
     INDEX=JMAX-J+1 2630
     DIAG(INDEX)=BCDEF(J) 2631
     SUP(INDEX)=CCDEF(J) 2632
     SUB(INDEX)=ACDEF(J) 2633
     CONST(INDEX)=DCDEF(J) 2634
30 CONTINUE 2635
   CALL TRID(JMAX) 2636
   DO 40 J=1,JMAX 2637
     L=JMAX-J+1 2638
     DE(K,J+1)=DE(K,J+1)+CONST(L) 2639
40 CONTINUE 2640
   RETURN 2641
   END 2642
   FUNCTION GAMM(I,J) 2643
C 2644
C 2645
C 2646
C 2647
C 2648
C 2649
C 2650
   GAMM=1.15 2651
   RETURN 2652
   END 2653
   FUNCTION RGAS(P,T) 2654
C 2655
C 2656
C 2657
C 2658
C 2659
C 2660
C 2661
   RGAS=4.184*10.**7*1.987/22. 2662
   RETURN 2663
   END 2664
   FUNCTION CV(I,J,IHALF,JHALF) 2665
C 2666
C 2667
C 2668
C 2669
C 2670
C 2671
C 2672
C 2673
   CV=1.67*10.**7 2674
   RETURN 2675
   END 2676
   FUNCTION CP(P,T) 2677
C 2678
C 2679
C 2680
C 2681
C 2682
C 2683
C 2684
   H=-0.22016E8-0.27793E2*P+0.23314E-4*P**2+(-0.16712E5+0.28226E-1*P-
10.23821E-7*P**2)*T+(0.44858E1-0.71655E-5*P+0.60721E-11*P**2)*T**2
   CP=H/T 2686
   RETURN 2687

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END                                                    2688
FUNCTION VIS(I, J, IHALF, JHALF)                    2689
C                                                    2690
C                                                    2691
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 2692
C COMPUTES LAMINAR VISCOSITY                       2693
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 2694
C                                                    2695
C                                                    2696
COMMON/CSTRSS/TRRA(225), TZZA(225), TODA(225), TRZA(225), VISC, VISCO 2697
C                                                    2698
C                                                    2699
VISC=VISCO                                           2700
VIS=VISCO                                           2701
RETURN                                              2702
END                                                  2703
FUNCTION EDDY(I, J)                                  2704
C                                                    2705
C                                                    2706
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 2707
C EDDY COEFFICIENT FOR TURBULENT CALCULATION       2708
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 2709
C                                                    2710
C                                                    2711
EDDY=0.                                              2712
RETURN                                              2713
END                                                  2714
FUNCTION COND(K, J, KHALF, JHALF)                   2715
C                                                    2716
C                                                    2717
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 2718
C DEFINES THERMAL CONDUCTIVITY                     2719
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 2720
C                                                    2721
C                                                    2722
COMMON /CCALC/ BL, EMF, MCALC, NMAGN, NTHRM, IPOT, IDFN, IPTSF 2723
NTHRM=99999                                         2724
COND=0.                                             2725
RETURN                                              2726
END                                                  2727
FUNCTION SIG(I, J, IHALF, JHALF, IN)                2728
C                                                    2729
C                                                    2730
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 2731
C DEFINES ELECTRICAL CONDUCTIVITY                  2732
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 2733
C                                                    2734
C                                                    2735
COMMON /CCALC/ BL, EMF, MCALC, NMAGN, NTHRM, IPOT, IDFN, IPTSF 2736
C                                                    2737
C                                                    2738
NMAGN=99999                                         2739
SIG=10, **(-10)                                    2740
RETURN                                              2741
END                                                  2742
FUNCTION BETA(I, J, IHALF, JHALF)                   2743
C                                                    2744
C                                                    2745
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 2746
C DEFINES HALL PARAMETER                            2747
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 2748
C                                                    2749
C                                                    2750
BETA=2.0                                            2751

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RETURN                                     2752
END                                         2753
FUNCTION B(I,J)                             2754
B=20000.                                    2755
RETURN                                     2756
END                                         2757
SUBROUTINE SECONO (A)                       2758
RETURN                                     2759
END                                         2760
SUBROUTINE PLOTTE                            2761
C                                           2762
C                                           2763
C                                           2764
C THE FOLLOWING SUBROUTINES EMPLOY EITHER STANDARD CALCOMP
C OR STROMBERG-CARLSON PLOT SUBROUTINES. IF CALCOMP ROUTINES ARE
C USED THEN THE SC ROUTINES MUST BE DUMMIED OUT (SEE TECHNICAL
C REPORT) OR IF THE SC ROUTINES ARE USED, THE CALCOMP ROUTINES
C ARE VOIDED.                               2768
C                                           2769
C                                           2770
C                                           2771
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C PLOT EXECUTIVE ROUTINE                    2772
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C                                           2773
C                                           2774
C                                           2775
COMMON /TPLT/ TPLTMI, TPLTMA, TPLTDE, TPLTDL, TZERO, T
COMMON /P1/ XGRAPH(45), ZGRAPH(225), XVELT(45, 225), ZVELT(45, 225),
1SH(45, 225), DR(45), DZ(225), NDLIN1(45, 225), NDLIN2(45, 225), ILOW,
1HIGH, JLOW, JHIGH, XLOW, XHIGH, ZLOW, ZHIGH, ML(10), MDIM(10), NCYCLE, ISC,
2DMN(525), XLF(225), YLF(225), IPLDW, IPHIGH, JPLDW, JPHIGH, XPT(50, 11),
3YPT(50, 11)
COMMON /P2/ L1, L2, L3, L4, MFRAME(10, 2), IPARAM, IRMIN(10), IRMAX(10), JR
1MIN(10), JRMAX(10), MPDDE(10), IPAR(10), IKT, IKM, MFR, IPART, NPIS, KLOG
COMMON /P3/ ZZ, LI1, LI2, LI3, LI4, E1, E2, E3, E4, ISYM, KL1, KL2, KL3, KL4, PL
10, IHMIN(20), IHMAX(20), JHMIN(20), JHMAX(20), MCODE(20), IHIST, ICHECK, M
2DVIE, IDET, IVEL, RPV, ILINE, MZODE(20), IDN(3), ISPAT, IZMIN(20), IZMAX(20
3), JZMIN(20), JZMAX(20), DUMVAR(40), WW, IVX, IVZ, INUMM
C                                           2788
C                                           2789
C *****
C 10 CONTINUE                               2791
C *****
C INITIALIZATION                           2793
C *****
IKT=0                                       2795
LI1=0                                       2796
LI3=0                                       2797
MFR=0                                       2798
PLD=0.                                     2799
KL1=0                                       2800
KL2=0                                       2801
KL3=0                                       2802
KL4=0                                       2803
C *****
C CARD INPUT DESCRIBING PLOTS DESIRED      2805
C *****
TZERO=0.                                   2807
CALL RDPLT                                  2808
REWIND 14                                    2809
20 CONTINUE                                 2810
IF (IHIST.LT.1.AND.ISPAT.LT.1) WRITE (6,150) IVEL,MDVIE,ISC
IF (IHIST.LT.1.AND.ISPAT.LT.1) CALL GRIDS
IF (IHIST.LT.1.AND.ISPAT.LT.1.AND.T.LE.TPLTMA) GO TO 20
C *****
C TIME HISTORY                             2814
C                                           2815

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C      *****
IF (IHIST.EQ.0) GO TO 80
IKT=0
IKM=IHIST
DO 70 KZ=1, IHIST
MFR=MFRAME(KZ,1)
IKT=IKT+1
PLQ=1.
KL1=IHMIN(KZ)
KL2=IHMAX(KZ)
KL3=JHMIN(KZ)
KL4=JHMAX(KZ)
C      *****
C      KL1, KL2 AND KL3, KL4 ARE THE CELL INDICES WHERE TIME HISTORIES
C      ARE RECORDED
C      *****
DO 60 IR=KL1, KL2
DO 60 JR=KL3, KL4
TZERO=-TPLTDE
ICODE=MCODE(KZ)
REWIND 14
KL=1
PRINT 160, KL1, KL2, KL3, KL4, ICODE
C      *****
C      BLOCKED DATA ON UNIT 14, 36 VARIABLES (TABLE C.1 OF TECHNICAL
C      REPORT) X 14 CELLS
C      *****
30 READ (14) (DMN(KX), KX=1, 504), T, NCYCLE, DT
DO 40 MX=1, 14
IND=(MX-1)*36
IA=DMN(IND+1)
JA=DMN(IND+2)
DUMVAR(21)=DMN(IND+21)
IC=IND+ICODE
DUMVAR(ICODE)=DMN(IC)
IF (T.LT.TPLTMI) GO TO 30
IF (IA.EQ.IR.AND.JA.EQ.JR) XLF(KL)=DUMVAR(21)
IF (IA.EQ.IR.AND.JA.EQ.JR) YLF(KL)=DUMVAR(ICODE)
IF (IA.EQ.IR.AND.JA.EQ.JR) KL=KL+1
IF (IA.EQ.IR.AND.JA.EQ.JR) PRINT 180, IA, JA, KL, XLF(KL-1), YLF(KL-1)
40 CONTINUE
IF (T.LT.TPLTMA) GO TO 30
TZERO=T
REWIND 14
C      *****
C      GRID IS ALSO PLOTTED
C      *****
50 CALL GRIDS
IF (T.LT.TZERO) GO TO 50
ICH=KL-2
NIP=0
CALL LABPLT (ICH, ICODE, IR, JR, NIP)
60 CONTINUE
70 CONTINUE
C      *****
C      SPATIAL DISTRIBUTION
C      *****
80 IF (ISPAT.EQ.0) GO TO 140
IKT=0
IKM=ISPAT
DO 130 I=1, ISPAT
MFR=MFRAME(I, 2)
IKT=IKT+1
IDIST=3

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IF (MDIM(1).EQ.2) IDIST=2	2880
PLD=2.	2881
KL1=IZMIN(1)	2882
KL2=IZMAX(1)	2883
KL3=JZMIN(1)	2884
KL4=JZMAX(1)	2885
TZERO=0.	2886
ICCODE=MZODE(1)	2887
REWIND 14	2888
KL=1	2889
PRINT 170, KL1, KL2, KL3, KL4, ICCODE, IDIST	2890
90 READ (14) (DMN(KX), KX=1, 504), T, NCYCLE, DT	2891
IF (T.LT.TPLTMI) GO TO 90	2892
SUM=T-TPLTDL-TZERO	2893
IF (SUM.LT.0.) GO TO 90	2894
DO 100 MX=1, 14	2895
IND=(MX-1)*36	2896
IA=DMN(IND+1)	2897
JA=DMN(IND+2)	2898
IC=IND+ICCODE	2899
IDG=3	2900
IF (IDIST.EQ.2) IDG=4	2901
DUMVAR(ICCODE)=DMN(IC)	2902
DUMVAR(IDIST)=DMN(IND+IDG)	2903
IF (IDIST.EQ.3.AND. IA.GE. KL1.AND. IA.LE. KL2.AND. JA.EQ. KL3) XLF(KL)=	2904
1DUMVAR(IDIST)	2905
IF (IDIST.EQ.3.AND. IA.GE. KL1.AND. IA.LE. KL2.AND. JA.EQ. KL3) YLF(KL)=	2906
1DUMVAR(ICCODE)	2907
IF (IDIST.EQ.3.AND. IA.GE. KL1.AND. IA.LE. KL2.AND. JA.EQ. KL3) KL=KL+1	2908
IF (IDIST.EQ.3.AND. IA.GE. KL1.AND. IA.LE. KL2.AND. JA.EQ. KL3) PRINT 18	2909
10, IA, JA, KL, XLF(KL-1), YLF(KL-1)	2910
IF (IDIST.EQ.2.AND. JA.GE. KL3.AND. JA.LE. KL4.AND. IA.EQ. KL1) XLF(KL)=	2911
1DUMVAR(IDIST)	2912
IF (IDIST.EQ.2.AND. JA.GE. KL3.AND. JA.LE. KL4.AND. IA.EQ. KL1) YLF(KL)=	2913
1DUMVAR(ICCODE)	2914
IF (IDIST.EQ.2.AND. JA.GE. KL3.AND. JA.LE. KL4.AND. IA.EQ. KL1) KL=KL+1	2915
IF (IDIST.EQ.2.AND. JA.GE. KL3.AND. JA.LE. KL4.AND. IA.EQ. KL1) PRINT 18	2916
10, IA, JA, KL, XLF(KL-1), YLF(KL-1)	2917
IF (IDIST.EQ.3.AND. IA.EQ. KL2.AND. JA.EQ. KL3) GO TO 110	2918
IF (IDIST.EQ.2.AND. JA.EQ. KL4.AND. IA.EQ. KL1) GO TO 110	2919
100 CONTINUE	2920
GO TO 90	2921
110 CONTINUE	2922
TZERO=T	2923
REWIND 14	2924
120 CALL GRIDS	2925
IF (T.LT.TZERO) GO TO 120	2926
ICH=KL-2	2927
NX=MDIM(1)	2928
CALL LABPLT (ICH, ICCODE, IR, JR, NX)	2929
KL=1	2930
IF (T.GT.TPLTMA) GO TO 130	2931
GO TO 90	2932
130 CONTINUE	2933
140 CONTINUE	2934
IF (INUMM.EQ.1) GO TO 10	2935
CALL PLOT (X, Y, 999)	2936
RETURN	2937
C	2938
C	2939
150 FORMAT (10X, 100(1H*), /, 25X, 25H GRID PLOT , 7HIVEL = ,	2940
13X, 13, 5X, 8HMOVIE = , 3X, 13, 5X, 6HISC = , 3X, 13, /, 10X, 100(1H*))	2941
160 FORMAT (10X, 100(1H*), /, 25X, 25H TEMPORAL DISTRIBUTION , /, 20X, 30H	2942
1 KL1, KL2, KL3, KL4, ICCODE , 6(2X, 13), /, 10X, 100(1H*))	2943

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170 FORMAT (10X,100(1H*),/,25X,25H SPATIAL DISTRIBUTION ,/,20X,30H      2944
1 KL1,KL2,KL3,KL4,ICODE,1DIST,6(2X,13),/,10X,100(1H*))                2945
180 FORMAT (21H IA,JA,KL,XLF,YLF ,3(2X,13),2(1X,E12.4))                2946
END                                                                        2947
SUBROUTINE RDPLT                                                            2948
C                                                                           2949
C                                                                           2950
C                                                                           2951
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX  2952
C READS CARD INPUT FOR PLOTTING                                           2953
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX  2954
C                                                                           2955
COMMON /COUTP/ TITLE(15),KPDEL,JPDEL,NPLOT,NPRN,NDIGPL,NGRAPH           2956
COMMON /TPLT/ TPLTMI,TPLTMA,TPLTDE,TPLTDL,TZERO,T                       2957
COMMON/P1/XGRAPH(45),ZGRAPH(225),XVELT(45,225),ZVELT(45,225),          2958
1SH(45,225),DR(45),DZ(225),NOLIN1(45,225),NOLIN2(45,225),ILOW,        2959
1HIGH,JLOW,JHIGH,XLOW,XHIGH,ZLOW,ZHIGH,ML(10),MDIM(10),NCYCLE,ISC,     2960
2DMN(525),XLF(225),YLF(225),IPLW,IPHIGH,JPLW,JPHIGH,XPT(50,11),      2961
3YPT(50,11)                                                                2962
COMMON /P2/ L1,L2,L3,L4,MFRAME(10,2),IPARAM,IRMIN(10),IRMAX(10),JR     2963
1MIN(10),JRMAX(10),MPDDE(10),IPAR(10),IKT,IKM,MFR,IPART,NPTS,KLOG      2964
COMMON /P3/ ZZ,L11,L12,L13,L14,E1,E2,E3,E4,ISYM,KL1,KL2,KL3,KL4,PL     2965
1D,IHMIN(20),IHMAX(20),JHMIN(20),JHMAX(20),MCODE(20),IHIST,ICHECK,M    2966
2DVE,IDET,IVEL,RPV,ILINE,MZDDE(20),IDN(3),ISPAT,IZMIN(20),IZMAX(20)   2967
3),JZMIN(20),JZMAX(20),DUMVAR(40),WW,IVX,IVZ,INUMM                    2968
DATA IKQ/O/                                                                2969
C                                                                           2970
C                                                                           2971
IKQ=IKQ+1                                                                    2972
IF (IKQ.EQ.1) TZ=T                                                            2973
KL1=0                                                                           2974
KL2=0                                                                           2975
KL3=0                                                                           2976
KL4=0                                                                           2977
ICHECK=0                                                                      2978
C *****                                                                2979
C IHIST= NUMBER OF TIME HISTORY CARDS                                         2980
C RPV=RASTERS/UNIT VELOCITY,CURRENT,ETC.                                     2981
C ISPAT=NUMBER OF SPATIAL CARDS                                              2982
C IPARAM=NUMBER OF PARAMETERS ON SAME PLOT                                   2983
C ILINE=NUMBER OF LINE CARDS (USUSALLY 2)                                   2984
C IVEL =0 ,NO VELOCITY VECTORS.....IVEL =1,VELOCITY VECTORS              2985
C MOVIE=0, NO MOVIE.....MOVIE=1, MOVIE.....MOVIE=3, CONTOUR MAP          2986
C NCODE = 1 (X) = 2 (Z)                                                       2987
C ISC=-1, SHADING.....ISC = 0 NO SHADING                                    2988
C NSHADE = DEGREE OF SHADING (1=DARKEST,10=LIGHTEST)                       2989
C ISYM=0 (NO MIRROR IMAGE), =1 (MIRROR IMAGE ABOUT X - AXIS) =2 (        2990
MIRROR IMAGE ABOUT Z - AXIS)                                                2991
C IDET=1,JUST GRID WITHOUT AXIA); IDET=3,PUNCHED CARDS OF SHADE/        2992
3-D/CONTOUR Z (SH) VALUES; IDET=5, 3-D PERSPECTIVE                       2993
C MDIM=1(X-DIRECTION),2(Z-DIRECTION) IN SPATIAL DISTRIBUTION PLOTS.        2994
C MCODE AND MZDDE ( TIME / SPATIAL DISTRIBUTION VARIABLES ) SELECTED      2995
C FROM BELOW.....TABLE C.1 IN AEDC TR-77-105                               2996
C E1= MINIMUM VALUE FOR SHADING, E2= MAXIMUM VALUE FOR SHADING            2997
C L11= VARIABLE TO BE SHADED, L12= LINEAR(0), LOGARITHMIC(1)              2998
C L13 = 1 IF HALF PLOT IS SHADED AND HALF PLOT IS VECTORS                 2999
C NOTE THAT SHADING IMPLIES 3-D PERSPECTIVE AND CONTOUR MAPPING ALSO      3000
3 R      8 V      13 MACH 18 TZZ 23 VISC 28 GAMMA 33 PHI                 3001
5 DR     10 E     15 M     20 TRZ 25 BZ 30 - 35 COND(T)                 3002
6 DZ     11 INT   16 BD    21 TIME 26 JR 31 TEMP 36 VDRT                 3003
7 U      12 C     17 TRR 22 DT 27 JZ 32 CV                               3004
C *****                                                                3005
WRITE (6,170) (TITLE(I),I=1,15)                                           3006
READ 180, MOVIE,IHIST,ISPAT,IPARAM,ILINE,ISC,IDET,ISYM,IVEL,RPV,IP      3007

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1ART	3008
PRINT 190, MOVIE, IHIST, ISPAT, IPARAM, ILINE, ISC, IDET, ISYM, IVEL, RPV, I	3009
1PART	3010
READ 200, ILOW, IHIGH, JLOW, JHIGH, L1, L2, L3, L4, JPDEL, KPDEL	3011
IF (JPDEL.EQ.0) JPDEL=1	3012
IF (KPDEL.EQ.0) KPDEL=1	3013
IF (L1.EQ.0) PRINT 220, ILOW, IHIGH, JLOW, JHIGH, JPDEL, KPDEL	3014
IF (L1.NE.0) PRINT 210, ILOW, IHIGH, JLOW, JHIGH, L1, L2, L3, L4	3015
IF (L1.EQ.0) L1=ILOW	3016
IF (L2.EQ.0) L2=IHIGH	3017
IF (L3.EQ.0) L3=JLOW	3018
IF (L4.EQ.0) L4=JHIGH	3019
DO 10 K1=1, IHIGH	3020
DO 10 J1=1, JHIGH	3021
SH(K1, J1)=0.	3022
NOLINI(K1, J1)=0	3023
NOLIN2(K1, J1)=0	3024
10 CONTINUE	3025
READ 230, ZLOW, ZHIGH, XLOW, XHIGH	3026
PRINT 240, ZLOW, ZHIGH, XLOW, XHIGH	3027
IF (IPART.EQ.0) GO TO 20	3028
READ (5, 140) IPLow, IPHIGH, JPLow, JPHIGH, NPTS	3029
WRITE (6, 150) IPLow, IPHIGH, JPLow, JPHIGH, NPTS	3030
20 CONTINUE	3031
C *****	3032
C VECTORS	3033
C *****	3034
IF (IVEL.EQ.0) GO TO 30	3035
READ 250, IVX, IVZ, KLOG	3036
PRINT 260, IVX, IVZ, KLOG	3037
30 CONTINUE	3038
C *****	3039
C TIME HISTORY CARDS	3040
C *****	3041
IF (IHIST.EQ.0) GO TO 50	3042
PRINT 270	3043
DO 40 I=1, IHIST	3044
READ 290, IHMIN(I), IHMAX(I), JHMIN(I), JHMAX(I), MCODE(I), MFRAME(I, 1)	3045
PRINT 280, IHMIN(I), IHMAX(I), JHMIN(I), JHMAX(I), MCODE(I), MFRAME(I, 1)	3046
1)	3047
MCODE(I)=MCODE(I)	3048
40 CONTINUE	3049
C *****	3050
C ELIMINATING LINES IN GRIDS	3051
C *****	3052
50 IF (ILINE.EQ.0) GO TO 80	3053
PRINT 300	3054
DO 70 N=1, ILINE	3055
READ 290, ISMIN, ISMAX, JSMIN, JSMAX, NCODE	3056
PRINT 310, ISMIN, ISMAX, JSMIN, JSMAX, NCODE	3057
DO 60 I=ILOW, IHIGH	3058
DO 60 J=JLOW, JHIGH	3059
IF (NCODE.EQ.1.AND.I.GE.ISMIN.AND.I.LE.ISMAX.AND.J.GE.JSMIN.AND.J.	3060
1LE.JSMAX) NOLINI(I, J)=1	3061
IF (NCODE.EQ.2.AND.I.GE.ISMIN.AND.I.LE.ISMAX.AND.J.GE.JSMIN.AND.J.	3062
1LE.JSMAX) NOLIN2(I, J)=1	3063
60 CONTINUE	3064
70 CONTINUE	3065
C *****	3066
C SPATIAL DISTRIBUTION CARDS	3067
C *****	3068
80 IF (ISPAT.EQ.0) GO TO 100	3069
PRINT 320	3070
DO 90 N=1, ISPAT	3071

```

READ 340, IZMIN(N), IZMAX(N), JZMIN(N), JZMAX(N), MZODE(N), MFRAME(N, 2) 3072
PRINT 330, IZMIN(N), IZMAX(N), JZMIN(N), JZMAX(N), MZODE(N), MFRAME(N, 2) 3073
1) 3074
MDIM(N)=2 3075
IF (IZMIN(N).NE. IZMAX(N)) MDIM(N)=1 3076
MZODE(N)=MZODE(N) 3077
90 CONTINUE 3078
C ***** 3079
C SHADING ZONES 3080
C ***** 3081
100 CONTINUE 3082
IF (ISC.EQ.-1) READ 350, E1,E2,L11,L12,L13 3083
IF (ISC.EQ.-1) PRINT 360, E1,E2,L11,L12,L13 3084
C ***** 3085
C PARAMETRIC PLOTS 3086
C ***** 3087
IF (IPARAM.EQ.0) GO TO 120 3088
DO 110 N=1, IPARAM 3089
READ 290, IRMIN(N), IRMAX(N), JRMIN(N), JRMAX(N), MPODE(N) 3090
PRINT 160, IRMIN(N), IRMAX(N), JRMIN(N), JRMAX(N), MPODE(N) 3091
110 CONTINUE 3092
120 READ 370, TPLTMI, TPLTMA, TPLTDE, TPLTDL, INUMM 3093
IF (TPLTMA.GT. TZ) TPLTMA=0.99999* TZ 3094
IF (TPLTDL.GT. TZ) TPLTDL=0.99999* TZ 3095
IF (TPLTDE.GT. TZ) TPLTDE=0.99999* TZ 3096
T=0. 3097
C ***** 3098
C PLOT TIME STEPS 3099
C ***** 3100
C TZERO=- TPLTDE 3101
C TZERO=0. 3102
IF (TPLTDL.NE.0.) PRINT 380, TPLTMI, TPLTMA, TPLTDE, TPLTDL 3103
IF (TPLTDL.NE.0.) GO TO 130 3104
PRINT 390, TPLTMI, TPLTMA, TPLTDE 3105
130 RETURN 3106
C ***** 3107
C 3108
140 FORMAT (6(I5)) 3109
150 FORMAT (3X, 5HIPLOW, 2X, 6HIPHIGH, 3X, 5HJPLow, 2X, 6HJPHIGH, 4X, 4HNPTS, /, 3110
14X, I3, 6X, I3, 5X, I3, 6X, I3, 4X, I3) 3111
160 FORMAT (32H IRMIN IRMAX JRMIN JRMAX MPODE, /, 5(3X, I3)) 3112
170 FORMAT (1H1, ///, 15A4) 3113
180 FORMAT (9I5, 5X, E10.4, I5) 3114
190 FORMAT (78H MOVIE IHIST ISPAT IPARAM ILINE ISC IDE 3115
1T ISYM IVEL RPV, 10H IPART, /, 2X, I3, 8(5X, I3), 2X, E10.4, 2X 3116
2, I3) 3117
200 FORMAT (10I5) 3118
210 FORMAT (55H ILOW IHIGH JLOW JHIGH L1 L2 L3 L4 3119
1, /, 2X, 8(I3, 5X)) 3120
220 FORMAT (47H ILOW IHIGH JLOW JHIGH JPDEL KPDEL, /, 2X, 6( 3121
I13, 5X)) 3122
230 FORMAT (4F10.4) 3123
240 FORMAT (45H ZLOW ZHIGH XLOW XHIGH, /, 4(2X, E1 3124
10.4)) 3125
250 FORMAT (3I5) 3126
260 FORMAT (19H IVX IVZ KLOG, /, 3(3X, I3)) 3127
270 FORMAT (39H IHMIN IHMAX JHMIN JHMAX MCODE MFRAME) 3128
280 FORMAT (6(3X, I3)) 3129
290 FORMAT (6I5) 3130
300 FORMAT (32H ISMIN ISMAX JSMIN JSMAX NCODE) 3131
310 FORMAT (5(3X, I3)) 3132
320 FORMAT (39H IZMIN IZMAX JZMIN JZMAX MZODE MFRAME) 3133
330 FORMAT (6(3X, I3)) 3134
340 FORMAT (6I5) 3135

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350	FORMAT (2E10.4,3(5X,15))				3136
360	FORMAT (60H	E1	E2	L11	3137
	1 ,19H L12	L13,/,5X,E15.5,5X,E15.5,3(5X,15,5X))			3138
370	FORMAT (4F10.4,39X,11)				3139
380	FORMAT (46H TPLTMI	TPLTMA	TPLTDE	TPLTDL ,/,4(2X,E	3140
	110.4),///)				3141
390	FORMAT (36H TPLTMI	TLPTMA	TPLTDE	,/,3(2X,E10.4),///)	3142
	END				3143
	SUBROUTINE GRIDS				3144
C					3145
C					3146
C	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX				3147
C	DRAWS GRID, INITIATES SHADING, MAPPING, 3-D AND TRACER PLOTS				3148
C	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX				3149
C					3150
C					3151
	COMMON /CMESH/ KMAX, JMAX, KP1, JP1, KP2, JP2				3152
	COMMON /COUTP/ TITLE(15), KPDEL, JPDEL, NPLLOT, NPRN, NDIGPL, NGRAPH				3153
	COMMON /TPLT/ TPLTMI, TPLTMA, TPLTDE, TPLTDL, TZERO, T				3154
	COMMON /CBOUND/ DANGLE(225), IOBK(225), IOBL(225), IDYM(4), IAXI, IOBQ				3155
	COMMON /CMHD/ INSJ(225), DVOL T, BASEP, DPOT, SPACE, SPINSL, JPLMIN, JPLMAX				3156
	COMMON /CCALC/ BL, EMF, MCALC, NMAGN, NTHRM, IPOT, IDFN, IPTSF				3157
	COMMON /CGRID/ R(45), RD(45), Z(225), FR(45), FZ(225), XF(45), ZMIN, RMIN, D				3158
	IZO, DRO, IGRAPH(225), NBOUND				3159
	COMMON /CINIT/ RHDO, VZ, VR, BO, BRO, BZO, EO, PHIO, PERMO, VELOC, ARFV, PERM				3160
	1, NVECT, NPDIM				3161
	COMMON /MOVE/ XX(4), YY(4)				3162
	COMMON /PI/ XGRAPH(45), ZGRAPH(225), XVELT(45,225), ZVELT(45,225),				3163
	1SH(45,225), DR(45), DZ(225), NOLINI(45,225), NOLIN2(45,225), ILOW,				3164
	1HIGH, JLOW, JHIGH, XLOW, XHIGH, ZLOW, ZHIGH, ML(10), MDIM(10), NCYCLE, ISC,				3165
	2DMN(525), XLF(225), YLF(225), IPLDW, IPHIGH, JPLDW, JPHIGH, XPT(50,11),				3166
	3YPT(50,11)				3167
	COMMON /P2/ L1,L2,L3,L4, MFRAME(10,2), IPARAM, IRMIN(10), IRMAX(10), JR				3168
	1MIN(10), JRMAX(10), MPDDE(10), IPAR(10), IKT, IKM, MFR, IPART, NPTS, KLOG				3169
	COMMON /P3/ ZZ, L11, L12, L13, L14, E1, E2, E3, E4, ISYM, KL1, KL2, KL3, KL4, PL				3170
	10, IHMIN(20), IHMAX(20), JHMIN(20), JHMAX(20), MCODE(20), IHIST, ICHECK, M				3171
	2DVIE, IDET, IVEL, RPV, ILINE, MZDDE(20), IDN(3), ISPAT, IZMIN(20), IZMAX(20				3172
	3), JZMIN(20), JZMAX(20), DUMVAR(40), WW, IVX, IVZ, INUMM				3173
	DIMENSION XGEO(45), ZGEO(225), XP(2,2), YP(2,2), TP(2,2), LL(200),				3174
	IS(200), TLABEL(102), INSND(225), IZZ(225)				3175
	REAL*8 R, RD				3176
	EQUIVALENCE (XGRAPH, XGEO), (ZGRAPH, ZGEO)				3177
	DATA LL/200*0/				3178
	DATA TLABEL/4H R-, 4HRADI, 4HAL ,4H Z-, 4HAXIA, 4HL ,4H DE, 4HLTA				3179
	1-, 4HR ,4H DE, 4HLTA-, 4HZ ,4H VEL, 4HOCIT, 4HY-Z ,4H VEL, 4HOCIT, 4				3180
	2HY-R ,4H PR, 4HESSU, 4HRE ,4HTOTA, 4HL EN, 4HERGY, 4H INT, 4HERNA, 4HL				3181
	3EN, 4H SPE, 4HED S, 4HDUND, 4H MA, 4HCH N, 4HD ,4H D, 4HENSI, 4HTY ,				3182
	44H ,4HMASS, 4H ,4H MA, 4HGN I, 4HND O, 4H ,4H TRR, 4H ,4H				3183
	5 ,4H TZZ, 4H ,4H ,4H TOD, 4H ,4H ,4H TRZ, 4H ,4H				3184
	6, 4H ER, 4H ,4H ,4H EZ, 4H ,4H VI, 4HSCDS, 4HITY ,4HMAGN, 4H				3185
	7 FLD, 4H R ,4HMAGN, 4H FLD, 4H Z ,4H CUR, 4HRENT, 4H-R ,4H CUR, 4HREN				3186
	8T, 4H-Z ,4H C, 4HP/CV, 4H ,4H CON, 4HD EL, 4HECTR, 4H ,4H ,4				3187
	9H ,4HTEMP, 4HERAT, 4HURE ,4HSP H, 4HEAT ,4HVOL ,4H POT, 4HENTI, 4HAL				3188
	\$,4HHALL, 4H PAR, 4HMTER, 4H CON, 4HD TH, 4HERML, 4H VDR, 4HTICI, 4HTY /				3189
					3190
C					3191
C					3192
	XX(3)=0.				3193
	XX(4)=1.				3194
	YY(3)=0.				3195
	YY(4)=1.				3196
	IFRT=1				3197
	IBACK=JHIGH				3198
	DD 10 KS=1, JHIGH				3199
	10 INSND(KS)=-1				3199

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SHDBND=4 3200
IF (MFR.EQ.1) RETURN 3201
IF (IPDT.EQ.0) GO TO 20 3202
ISP=SPINSL+SPACE 3203
JIP=0 3204
ICND=1 3205
IELECT=SPACE 3206
20 CONTINUE 3207
LIMIT=0 3208
***** 3209
READING FROM UNIT 14 3210
***** 3211
30 READ (14) (DMN(KX),KX=1,504),T,NCYCLE,DT 3212
DO 60 L=1,14 3213
IF (LIMIT.EQ.1) GO TO 60 3214
LA=(L-1)*36 3215
II=DMN(LA+1) 3216
JJ=DMN(LA+2) 3217
IF (JJ.EQ.1) XGRAPH(II)=DMN(LA+3) 3218
ZGRAPH(JJ)=DMN(LA+4) 3219
XVELT(II,JJ)=DMN(LA+8) 3220
ZVELT(II,JJ)=DMN(LA+7) 3221
IF (IVEL.NE.0) XVELT(II,JJ)=DMN(LA+IVX) 3222
IF (IVEL.NE.0) ZVELT(II,JJ)=DMN(LA+IVZ) 3223
DO 40 KR=3,36 3224
LAF=LA+KR 3225
40 DUMVAR(KR)=DMN(LAF) 3226
IF (DUMVAR(30).EQ.2.) NDLINI(II,JJ)=2 3227
IF (DUMVAR(30).EQ.2.) NDLIN2(II,JJ)=2 3228
IF (IPDT.EQ.0) GO TO 50 3229
IF (JJ.LT.JPLMIN.OR.JJ.GT.JPLMAX) GO TO 50 3230
IPL1=KP2+1-IGRAPH(JJ) 3231
IPL2=IGRAPH(JJ) 3232
IF (II.NE.IPL2) GO TO 50 3233
JIP=JIP+1 3234
IF (JIP.LE.IELECT) INSND(JJ)=ICND 3235
IF (JIP.GT.IELECT) INSND(JJ)=0 3236
IF (JIP.EQ.ISP) JIP=0 3237
IF (JIP.EQ.0) ICND=ICND+1 3238
50 CONTINUE 3239
DR(II)=DUMVAR(5) 3240
DZ(JJ)=DUMVAR(6) 3241
IF (II.EQ.L2.AND.JJ.EQ.L4) LIMIT=1 3242
***** 3243
DETERMINING SHADE, CONTOUR OR 3-D VARIABLE VALUE (SH) 3244
***** 3245
IF (ISC.NE.-1) GO TO 60 3246
IF (NDLINI(II,JJ).GT.2) GO TO 60 3247
IF (LI2.EQ.0) DELTA=(E2-E1)/10. 3248
IF (LI2.EQ.1) DELTA=(ALOG10(E2)-ALOG10(E1))/10. 3249
SH(II,JJ)=0. 3250
IF (LI1.NE.33) DUMVAR(LI1)=ABS(DUMVAR(LI1)) 3251
IF (LI2.EQ.1.AND.DUMVAR(LI1).LE.1..AND.LI1.NE.33) GO TO 60 3252
IF (LI2.EQ.0) SH(II,JJ)=(DUMVAR(LI1)-E1)/DELTA 3253
IF (LI2.EQ.1) SH(II,JJ)=(ALOG10(DUMVAR(LI1))-ALOG10(E1))/DELTA 3254
IF (SH(II,JJ).LT.-2.5) SH(II,JJ)=-2.5 3255
IF (SH(II,JJ).GT.12.5) SH(II,JJ)=12.5 3256
60 CONTINUE 3257
***** 3258
CONTOUR LIMITS 3259
***** 3260
IF (LIMIT.EQ.0) GO TO 30 3261
IF (ISC.NE.-1) GO TO 80 3262
S(1)=E1 3263

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	DD 70 KM=2,200	3264
	S(KM)=S(KM-1)+DELTA/4.	3265
70	CONTINUE	3266
80	CONTINUE	3267
	ITOP=0	3268
	IHALF=L2/2	3269
	IF (XGRAPH(IHALF).GT.0.) ITOP=1	3270
	IF (T.LT.TPLTMI) RETURN	3271
	SUM=T-TPLTDE-TZERO	3272
	IF (IHIST.LT.1.AND.ISPAT.LT.1.AND.SUM.LT.0.) RETURN	3273
	IF (IHIST.LT.1.AND.ISPAT.LT.1) TZERO=T	3274
	IF (IHIST.GE.1.AND.T.LT.TZERO) RETURN	3275
	IF (ISPAT.GE.1.AND.T.LT.TZERO) RETURN	3276
	IBACK=0	3277
	IFRT=0	3278
	IF (IOBQ.EQ.0) GO TO 170	3279
C	*****	3280
C	DEFINING SOLID BOUNDARY AND ELECTRODES FOR GRID IDENTIFICATION	3281
C	*****	3282
	DD 120 J5=JLOW,JHIGH	3283
	K5=IGRAPH(J5)	3284
	KOBL=KP2+1-IGRAPH(J5)	3285
	IF (K5.GT.L2) GO TO 120	3286
	IF (K5.LE.L2.AND.NVECT.EQ.2) NDLINI(KOBL,J5)=5	3287
	IF (K5.LE.L2) NDLINI(K5,J5)=5	3288
	IF (K5.EQ.L2) GO TO 100	3289
	KIX=K5+1	3290
	DD 90 KX=KIX,IHIGH	3291
	LX=KP2+1-KX	3292
	IF (J5.EQ.JLOW.OR.J5.EQ.JHIGH) GO TO 90	3293
	IF (NDLINI(KX,J5+1).EQ.1.OR.NDLINI(KX,J5-1).EQ.1) NDLINI(KX,J5)=5	3294
	IF (NDLINI(KX,J5+1).EQ.1.AND.NVECT.EQ.2) NDLINI(LX,J5)=5	3295
	IF (NDLINI(KX,J5-1).EQ.1.AND.NVECT.EQ.2) NDLINI(LX,J5)=5	3296
90	CONTINUE	3297
100	CONTINUE	3298
	IF (IPDT.EQ.0) GO TO 110	3299
	IF (J5.GE.JPLMIN.AND.J5.LE.JPLMAX.AND.INSND(J5).EQ.0) NDLINI(K5,J5	3300
	1)=3	3301
	IF (J5.GE.JPLMIN.AND.J5.LE.JPLMAX.AND.INSND(J5).EQ.0) NDLINI(K5,J5	3302
	1)=5	3303
	IF (J5.GE.JPLMIN.AND.J5.LE.JPLMAX.AND.INSND(J5).EQ.0) NDLINI(K5,J5	3304
	1)=5	3305
	IF (J5.GE.JPLMIN.AND.J5.LE.JPLMAX.AND.INSND(J5).NE.0) NDLINI(K5,J5	3306
	1)=4	3307
	IF (NVECT.NE.2) GO TO 110	3308
	IF (J5.GE.JPLMIN.AND.J5.LE.JPLMAX.AND.INSND(J5).EQ.0) NDLINI(KOBL,	3309
	1J5)=3	3310
	IF (J5.GE.JPLMIN.AND.J5.LE.JPLMAX.AND.INSND(J5).EQ.0) NDLINI(KOBL,	3311
	1J5)=5	3312
	IF (J5.GE.JPLMIN.AND.J5.LE.JPLMAX.AND.INSND(J5).EQ.0) NDLINI(KOBL,	3313
	1J5)=5	3314
	IF (J5.GE.JPLMIN.AND.J5.LE.JPLMAX.AND.INSND(J5).NE.0) NDLINI(KOBL,	3315
	1J5)=4	3316
110	CONTINUE	3317
	IF (K5.LE.L2) IBACK=J5	3318
	IF (K5.LE.L2.AND.IFRT.EQ.0) IFRT=J5	3319
	IF (IOBQ.NE.0.AND.NDLINI(L2,J5).GT.1.AND.ISYM.NE.2) NDLINI(L2,J5)=	3320
	15	3321
	IF (IOBQ.NE.0.AND.NDLINI(L2,J5).GT.1.AND.ISYM.EQ.2.AND.ITOP.EQ.1)	3322
	1NDLINI(L2,J5)=5	3323
	IF (IOBQ.NE.0.AND.NVECT.EQ.2) NDLINI(1,J5)=5	3324
120	CONTINUE	3325
	MM=IGRAPH(IFRT)	3326
	DD 130 M6=MM,IHIGH	3327

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130 NDLINI(M6,IFRT)=5                               3328
    NN=IGRAPH(IBACK)                                  3329
    DO 140 N6=NN,IHIGH                                3330
140 NDLINI(N6,IBACK)=5                               3331
    IF (NVECT.NE.2) GO TO 170                         3332
    KFRT=KP2+1-IGRAPH(IFRT)                           3333
    KBCK=KP2+1-IGRAPH(IBACK)                          3334
    KLD=KP2+1-IHIGH                                    3335
    DO 150 M6=KLD,KFRT                                3336
150 NDLINI(M6,IFRT)=5                               3337
    DO 160 N6=KLD,KBCK                                3338
160 NDLINI(N6,IBACK)=5                               3339
170 CONTINUE                                          3340
    IF (NCYCLE.GT.1) GO TO 180                         3341
    IF (MOVIE.LT.5) GO TO 180                         3342
    CALL FRAMEV (3)                                    3343
    IDUM=0                                             3344
    CALL SYMBOL (2.,5.,.30,TITLE,0.,.30)              3345
180 CONTINUE                                          3346
    PRINT 550, NCYCLE,T,DT                             3347
    LSYM=-1                                            3348
C *****                                           3349
C PLOTTING GRIDS                                     3350
C *****                                           3351
C CALL FRAMEV (3)                                    3352
C *****                                           3353
C MARGIN LINES AND LABELLING                       3354
C *****                                           3355
CALL NXVDSB (1,ZLOW,ZHIGH,IIII)                       3356
CALL NXVDSB (2,XLOW,XHIGH,IIII)                       3357
IF (IDET.EQ.1) GO TO 220                               3358
CALL CHSIZV (2,2)                                     3359
TUB=T*10.,**3                                         3360
DO 190 KS=1,5                                         3361
IF (IHIST.GT.0.DR.ISPAT.GT.0) GO TO 210               3362
CALL CHSIZV (3,3)                                     3363
CALL SYMBOL (3.8,1.3,.10,11HTIME (MSEC),0.,11)       3364
DO 185 KW=1,15                                        3365
XCD=2.+KW*0.70                                       3366
185 CALL SYMBOL (XCD,9.3,.2,TITLE(KW),0.,4)           3367
CALL NUMBER (6.5,1.3,.2,TUB,0.,4)                    3368
CALL SYMBOL (4.8,1.0,.1,5HCYCLE,0.,5)                3369
CYCLE=NCYCLE                                          3370
CALL NUMBER (5.8,1.0,.1,CYCLE,0.,-1)                 3371
CALL CHSIZV (2,2)                                     3372
190 CONTINUE                                          3373
WRITE (6,540) TUB                                     3374
CALL SYMBOL (4.5,0.22,.12,12HZ-AXIAL (CM),0.,12)     3375
CALL SYMBOL (.45,4.5,.12,12HX-RADIAL (CM),90.,12)    3376
IF (LI1.EQ.0) GO TO 200                               3377
LI1=LI1                                               3378
JCODE=3*(LI1-3)+1                                     3379
CALL SYMBOL (1.75,9.0,.12,TLABEL (JCODE),0.,4)       3380
CALL SYMBOL (2.23,9.0,.12,TLABEL (JCODE+1),0.,4)    3381
CALL SYMBOL (2.71,9.0,.12,TLABEL (JCODE+2),0.,4)    3382
F1=E1                                                 3383
F2=E2                                                 3384
IF (LI1.EQ.33.AND.IPTSF.EQ.2) F1=F1*10.,**(-8)      3385
IF (LI1.EQ.33.AND.IPTSF.EQ.2) F2=F2*10.,**(-8)      3386
IF (LI2.EQ.1) F1=ALDG10(E1)                           3387
IF (LI2.EQ.1) F2=ALDG10(E2)                           3388
CALL NUMBER (1.5,8.75,.12,F1,0.,3)                   3389
CALL SYMBOL (2.3,8.75,.12,2HTD,0.,2)                 3390
CALL NUMBER (3.1,8.75,.12,F2,0.,3)                   3391

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IF (LI2.EQ.0) CALL SYMBOL (8.0,9.00.,12,10H LINEAR ,0.,10) 3392
IF (LI2.NE.0) CALL SYMBOL (8.00,9.0.,12,10H LOGARITHM,0.,10) 3393
200 CONTINUE 3394
DX=(ZHIG-H-ZLOW)/10. 3395
DY=(XHIG-H-XLOW)/10. 3396
LX=2 3397
LY=1 3398
210 CONTINUE 3399
C ***** 3400
C MIRROR IMAGE 3401
C ***** 3402
220 LSYM=LSYM+1 3403
IF (LSYM.EQ.0) GO TO 250 3404
DO 230 JEK=JLOW, JHIGH 3405
IF (ISYM.EQ.1) ZGEO(JEK)=-ZGRAPH(JEK) 3406
230 CONTINUE 3407
DO 240 IEK=ILOW, IHIGH 3408
IF (ISYM.EQ.2) XGEO(IEK)=-XGRAPH(IEK) 3409
240 CONTINUE 3410
250 CONTINUE 3411
DO 260 KLLL=1, IHIGH 3412
WRITE (6,470) (NOLINI(KLLL,LJJJ),LJJJ=1, JHIGH) 3413
260 CONTINUE 3414
C ***** 3415
C HORIZONTAL GRIDS 3416
C ***** 3417
ISEN=1 3418
IF (LSYM.EQ.1) ISEN=-1 3419
DO 280 LJ=JLOW, JHIGH 3420
IPP1=KP2+1-IGRAPH(LJ) 3421
DO 280 LI=ILOW, IHIGH 3422
IF (NOLINI(LI,LJ).EQ.1) GO TO 280 3423
ZG1=ZGRAPH(LJ)+DZ(LJ)/2. 3424
XG1=XGRAPH(LI)-DR(LI)/2.*ISEN 3425
ZG2=ZGRAPH(LJ)-DZ(LJ)/2. 3426
XG2=XGRAPH(LI)+DR(LI)/2.*ISEN 3427
CALL NXVDSB (3,ZG1,T,M1) 3428
CALL NXVDSB (4,XG1,T,M2) 3429
CALL NXVDSB (3,ZG2,T,M3) 3430
CALL NXVDSB (4,XG2,T,M4) 3431
IF (NVECT.EQ.2.AND.LI.EQ.IPP1) CALL LINEV (M1,M4,M3,M4) 3432
IF (LI.LT.IHIGH) GO TO 270 3433
CALL LINEV (M1,M4,M3,M4) 3434
270 CALL LINEV (M1,M2,M3,M2) 3435
280 CONTINUE 3436
C ***** 3437
C VERTICAL GRID LINES 3438
C ***** 3439
DO 310 LJ=JLOW, JHIGH 3440
DO 310 LI=ILOW, IHIGH 3441
CALL NXVDSB (3,ZGRAPH(LJ),T,MX1) 3442
CALL NXVDSB (4,XGRAPH(LI),T,MY1) 3443
IF (NOLIN2(LI,LJ).EQ.1) GO TO 290 3444
XG1=XGRAPH(LI)-DR(LI)/2.*ISEN 3445
ZG1=ZGRAPH(LJ)-DZ(LJ)/2. 3446
XG2=XGRAPH(LI)+DR(LI)/2.*ISEN 3447
ZG2=ZGRAPH(LJ)+DZ(LJ)/2. 3448
CALL NXVDSB (3,ZG1,T,M1) 3449
CALL NXVDSB (3,ZG2,T,M3) 3450
CALL NXVDSB (4,XG1,T,M2) 3451
CALL NXVDSB (4,XG2,T,M4) 3452
IF (LJ.EQ.JHIGH) CALL LINEV (M3,M2,M3,M4) 3453
IPIC=0 3454
IF (LJ.LT.JHIGH) IPIC=1 3455

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IF (IPIC.EQ.1.AND.IGRAPH(LJ).NE.IGRAPH(LJ+1)) CALL LINEV (M3,M2,M3
1,M4)
CALL LINEV (M1,M2,M1,M4)
290 CONTINUE
C *****
C VECTORS
C *****
IF (ISC.EQ.-1.AND.LI3.EQ.1.AND.LSYM.EQ.0) GO TO 300
IF (IVEL.NE.1) GO TO 300
IF (MOD(LI,KPDEL).NE.0.OR.MOD(LJ,JPDEL).NE.0) GO TO 300
IF (NOLINI(LI,LJ).GT.1) GO TO 300
ZZ1=1.
ZZ2=1.
IF (LSYM.EQ.1.AND.ISYM.EQ.1) ZZ1=-1.
IF (LSYM.EQ.1.AND.ISYM.EQ.2) ZZ2=-1.
IF (LSYM.EQ.1.AND.XGRAPH(LI).EQ.0.) GO TO 300
ZCOMP=ZVELT(LI,LJ)*RPV*ZZ1
XCOMP=XVELT(LI,LJ)*RPV*ZZ2
IF (KLOG.NE.0) XCOMP=ALOG10(XVELT(LI,LJ))*RPV*ZZ2
IF (KLOG.NE.0) ZCOMP=ALOG10(ZVELT(LI,LJ))*RPV*ZZ1
SUM=ABS(ZCOMP)+ABS(XCOMP)
IF (SUM.LT.1.) GO TO 300
IXC=XCOMP
IZC=ZCOMP
IZC=MX1-IZC
IXC=MY1-IXC
CALL LINEV (IZC,IXC,MX1,MY1)
CALL ARROW (MX1,MY1,M1,M2,XCOMP,ZCOMP)
300 CONTINUE
310 CONTINUE
C *****
C CONTOUR MAPPING AND SHADING
C *****
DO 390 LJ=JLOW,JHIGH
ISW=-1
DO 390 LI=LOW,IHIGH
ISW=-ISW
ZG1=ZGRAPH(LJ)-DZ(LJ)/2.
XG1=XGRAPH(LI)-DR(LI)/2.*ISEN
ZG2=ZGRAPH(LJ)+DZ(LJ)/2.
XG2=XGRAPH(LI)+DR(LI)/2.*ISEN
IUP=2*NOLINI(LI,LJ)-1
CALL NXVDSB (3,ZG1,T,M1)
CALL NXVDSB (4,XG1,T,M2)
CALL NXVDSB (3,ZG2,T,M3)
CALL NXVDSB (4,XG2,T,M4)
IF (ISC.NE.-1) GO TO 320
C *****
C COMPUTING X,Y,Z VALUES OF CONTOUR MAP..... CELL BE CELL
C *****
IF (MOVIE.EQ.0.AND.LI3.EQ.0) GO TO 320
IF (MOVIE.EQ.0.AND.LSYM.EQ.1) GO TO 320
IF (MOVIE.EQ.3.AND.LI3.NE.0.AND.LSYM.EQ.1) GO TO 320
IF (NOLINI(LI,LJ).GT.1) GO TO 320
XP(1,1)=M1/102.3
XP(1,2)=M1/102.3
XP(2,1)=M3/102.3
XP(2,2)=M3/102.3
YP(1,1)=M2/102.3
YP(2,1)=M2/102.3
YP(1,2)=M4/102.3
YP(2,2)=M4/102.3
I=1
J=1

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K=1 3520
L=1 3521
IF (LI.EQ.ILOW) I=0 3522
IF (LI.EQ.IHIGH) K=0 3523
IF (LJ.EQ.JLOW) J=0 3524
IF (LJ.EQ.JHIGH) L=0 3525
TP(1,1)=(SH(LI,LJ)+SH(LI-I,LJ)+SH(LI-I,LJ-J)+SH(LI,LJ-J))/4.*DELTA 3526
1+E1 3527
TP(1,2)=(SH(LI,LJ)+SH(LI+K,LJ)+SH(LI+K,LJ-J)+SH(LI,LJ-J))/4.*DELTA 3528
1+E1 3529
TP(2,1)=(SH(LI-I,LJ)+SH(LI-I,LJ+L)+SH(LI,LJ)+SH(LI,LJ+L))/4.*DELTA 3530
1+E1 3531
TP(2,2)=(SH(LI,LJ)+SH(LI,LJ+L)+SH(LI+K,LJ)+SH(LI+K,LJ+L))/4.*DELTA 3532
1+E1 3533
CALL LEVEL (TP,XP,YP,2,2,S,LL,200) 3534
320 CONTINUE 3535
C ***** 3536
C DRAWING CELL DIAGONALS 3537
C ***** 3538
IF (NOLINI(LI,LJ),LT.2) GO TO 340 3539
IF (NOLINI(LI,LJ),EQ.3.OR.NOLINI(LI,LJ),EQ.4) GO TO 340 3540
DO 330 IBD=1,IUP 3541
IF (IHIST.NE.O.OR.ISPAT.NE.O) ISW=0 3542
IF (ISW.EQ.-1.OR.NOLINI(LI,LJ),EQ.5) CALL LINEV (M1,M2,M3,M4) 3543
IF (ISW.EQ.+1.OR.NOLINI(LI,LJ),EQ.5) CALL LINEV (M3,M2,M1,M4) 3544
330 CONTINUE 3545
340 CONTINUE 3546
IF (IPOT.EQ.O) GO TO 380 3547
IF (NOLINI(LI,LJ),NE.4) GO TO 380 3548
C ***** 3549
C NUMBERING ELECTRODE-PAIRS 3550
C ***** 3551
PNUMB=INSND(LJ) 3552
350 IF (PNUMB.LT.10.) GO TO 360 3553
PNUMB=PNUMB-10. 3554
GO TO 350 3555
360 CONTINUE 3556
CM1=M2 3557
CM3=M4 3558
CHAR=(CM3-CM1)/160. 3559
CHAR=ABS(CHAR) 3560
MN1=M1+(M3-M1)/10 3561
MN2=M2+(M4-M2)/10 3562
MN4=M4+(M2-M4)/10 3563
XM1=MN1 3564
XM2=MN2 3565
IF (LSYM.EQ.1) XM2=MN4 3566
XM1=XM1/102.3+0.20*CHAR 3567
XM2=XM2/102.3+0.12*CHAR 3568
DO 370 MIS=1,6 3569
IF (NOLINI(LI,LJ),EQ.4) CALL NUMBER (XM1,XM2,CHAR,PNUMB,O.,-1) 3570
370 CONTINUE 3571
380 CONTINUE 3572
C ***** 3573
C ***** SHADING ***** 3574
C ***** 3575
IF (MOVIE.EQ.3) GO TO 390 3576
IF (LI3.EQ.1.AND.LSYM.EQ.O) GO TO 390 3577
IF (ISC.NE.-1.OR.NOLINI(LI,LJ),GT.1) GO TO 390 3578
Q=SH(LI,LJ) 3579
IF (Q.GT.10) Q=10. 3580
IF (Q.LT.O.) Q=0. 3581
IQ=Q 3582
IF (LSYM.EQ.O) CALL SHADE (M1,M2,M3,M4,IQ) 3583

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	IF (LSYM.EQ.1) CALL SHADE (M1,M2,M3,M4,IQ)	3584
390	CONTINUE	3585
C	*****	3586
C	SHADE LEGEND	3587
C	*****	3588
	IF (MOVIE.NE.0) GO TO 410	3589
	IF (ISC.NE.-1) GO TO 410	3590
	IF (LSYM.EQ.1) GO TO 410	3591
	DD 400 J=1,10	3592
	CK=J-1	3593
	DELTA=(E2-E1)/10.	3594
	CN1=E1+(J-1)*DELTA	3595
	CN2=CN1+DELTA	3596
	DD=2.*DR(1)	3597
	YB=XGRAPH(IHIGH)-DD*(J-1)	3598
	CALL NXVDSB (4,YB,T,M2)	3599
	YB=M2/102.3	3600
	XA=ZGRAPH(1)-20.*DZ(1)	3601
	CALL NXVDSB (3,XA,T,M1)	3602
	XA=M1/102.3	3603
	XB=XA+0.25	3604
	XC=XA+1.0	3605
	CALL NUMBER (XA,YB,0.1,CK,0.,-1)	3606
	IF (LI1.EQ.14) CALL NUMBER (XB,YB,0.1,CN1,0.,+4)	3607
	IF (LI1.EQ.14) CALL NUMBER (XC,YB,0.1,CN2,0.,+4)	3608
	IF (LI1.NE.14) CALL NUMBER (XB,YB,0.1,CN1,0.,+1)	3609
	IF (LI1.NE.14) CALL NUMBER (XC,YB,0.1,CN2,0.,+1)	3610
	XDD=ZGRAPH(1)-25.*DZ(1)	3611
	YD=XGRAPH(IHIGH)-DD*(J-1)-DD/4.	3612
	QZ=(J-1)*7	3613
	XD1=XDD+DD	3614
	YD1=YD+DD	3615
	CALL NXVDSB (3,XD,T,M1)	3616
	CALL NXVDSB (3,XD1,T,M3)	3617
	CALL NXVDSB (4,YD,T,M2)	3618
	CALL NXVDSB (4,YD1,T,M4)	3619
	XX1=M1/102.3	3620
	XX2=M3/102.3	3621
	YY1=M2/102.3	3622
	YY2=M4/102.3	3623
	CALL PLOT (XX1,YY1,+3)	3624
	CALL PLOT (XX2,YY1,+2)	3625
	CALL PLOT (XX2,YY2,+2)	3626
	CALL PLOT (XX1,YY2,+2)	3627
	CALL PLOT (XX1,YY1,+2)	3628
	CALL SHADE (M1,M2,M3,M4,J)	3629
400	CONTINUE	3630
410	CONTINUE	3631
	IF (LI3.EQ.1.AND.LSYM.EQ.0) GO TO 420	3632
	IF (IPART.NE.0) CALL PARTCL	3633
420	IF (ISYM.EQ.0) GO TO 430	3634
	IF (LSYM.EQ.0) GO TO 220	3635
430	IF (IDET.EQ.2) CALL LABPLT	3636
	IF (ISC.NE.-1,DR.IDET.NE.3) GO TO 460	3637
C	*****	3638
C	PUNCHED OUTPUT OF SH	3639
C	*****	3640
	PUNCH 480, IHIGH,JHIGH,NCYCLE,DZ(1),DR(1),ZGRAPH(1),XGRAPH(1),(TIT	3641
	ILE(I),I=1,8)	3642
	WRITE (6,490) IHIGH,JHIGH,NCYCLE,DZ(1),DR(1),ZGRAPH(1),XGRAPH(1),(3643
	ITITLE(I),I=1,8)	3644
	JCODE=3*(LI1-3)+1	3645
	PUNCH 500, E1,E2,TLABEL(JCODE),TLABEL(JCODE+1),TLABEL(JCODE+2)	3646
	WRITE (6,510) E1,E2,TLABEL(JCODE),TLABEL(JCODE+1),TLABEL(JCODE+2)	3647

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DD 450 I=ILOW,IHIGH                                3648
DD 440 LJ=JLOW,JHIGH                                3649
LI=IHIGH+ILOW-I                                     3650
IZZ(LJ)=SH(LI,LJ)                                   3651
IF (IZZ(LJ).GT.9) IZZ(LJ)=9                         3652
IF (IZZ(LJ).LT.0) IZZ(LJ)=0                         3653
440 CONTINUE                                         3654
PUNCH 520, (IZZ(J),J=1,JHIGH)                       3655
WRITE (6,530) (IZZ(J),J=1,JHIGH)                   3656
450 CONTINUE                                         3657
460 CONTINUE                                         3658
IF (IDET.EQ.5) CALL THREEED                         3659
RETURN                                               3660
C                                                    3661
C                                                    3662
C                                                    3663
470 FORMAT (10X,100I1)                               3664
480 FORMAT (13,13,14,4E10.4,7A4,A2)                 3665
490 FORMAT (10X,13,2X,13,2X,14,4(1X,E12.4),7A4,A2) 3666
500 FORMAT (2E10.4,3A4)                             3667
510 FORMAT (10X,2E10.4,5X,3A4)                     3668
520 FORMAT (80I1)                                    3669
530 FORMAT (5X,80I1)                                 3670
540 FORMAT (10X,11HTIME(MSEC),E12.4)                3671
550 FORMAT (8X,16H NCYCLE,T,DT ,14,2(1X,E12.4))     3672
END                                                  3673
SUBROUTINE LABPLT (ILIP,ICODE,IPLDT,JPLDT,MDIM)     3674
C                                                    3675
C                                                    3676
C                                                    3677
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 3678
C PLOTS TIME AND SPACE HISTORIES                   3679
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 3680
C                                                    3681
C                                                    3682
DIMENSION TLABEL(102), TLOB(102), IC(34), TLAB(3,3), SYMB(36)
COMMON /TPLT/ TPLTMI,TPLTMA,TPLTDE,TPLTDL,TZERO,T
COMMON /CDUTP/ TITLE(15),KPDEL,JPDEL,NPLOT,NPRN,NDIGPL,NGRAPH
COMMON /PI/XGRAPH(45),ZGRAPH(225),XVELT(45,225),ZVELT(45,225),
1SH(45,225),DR(45),DZ(225), NDLIN1(45,225),NDLIN2(45,225),ILOW,
11HIGH,JLOW,JHIGH,XLOW,XHIGH,ZLOW,ZHIGH,ML(10),IDIM(10),NCYCLE,ISC,
2DMN(525),X (225),Y (225),IPLW,IPHIGH,JPLW,JPHIGH,XPT(50,11),
3YPT(50,11)
COMMON /P2/ L1,L2,L3,L4,MFRAME(10,2),IPARAM,IRMIN(10),IRMAX(10),JR
1MIN(10),JRMAX(10),MPDDE(10),IPAR(10),IKT,IKM,MFR,IPART,NPTS,KLDG
COMMON /P3/ ZZ,L11,L12,L13,L14,E1,E2,E3,E4,ISYM,KL1,KL2,KL3,KL4,PL
1D,IHMIN(20),IHMAX(20),JHMIN(20),JHMAX(20),MCODE(20),IHIST,ICHECK,M
2DVIE,IDET,IVEL,RPV,ILINE,MZDDE(20),IDN(3),ISPAT,IZMIN(20),IZMAX(20
3),JZMIN(20),JZMAX(20),DUMVAR(40),WW,IVX,IVZ,INUMM
C                                                    3690
C                                                    3691
C                                                    3692
C                                                    3693
C                                                    3694
C                                                    3695
C                                                    3696
C DATA SYMB/1HI,1HJ,1HR,1HZ,1H ,1H ,1HU,1HV,1HP,1HE,1HI,1HC,1HM,1HR,
11HM,1HB,1HT,1HT,1HT,1HT,1H ,1HV,1HP,1HS,1HJ,1HJ,1HG,1HN,1HT,1H
2I,1H ,1H ,1H ,1H /
C DATA TVS/4H VS /
C                                                    3697
C                                                    3698
C                                                    3699
C                                                    3700
C                                                    3701
C DATA TLABEL/4H R-,4HRADI,4HAL ,4H Z-,4HAXIA,4HL ,4H DE,4HLTA
1-,4HR ,4H DE,4HLTA-,4HZ ,4H VEL,4HOCIT,4HY-Z ,4H VEL,4HOCIT,4
2HY-R ,4H PR,4HESSU,4HRE ,4HTOTA,4HL EN,4HERGY,4H INT,4HERNA,4HL
3EN,4H SPE,4HED S,4HOUND,4H MA,4HCH N,4HO ,4H D,4HENSI,4HTY ,
44H ,4HMASS,4H ,4H MA,4HGN I,4HND O,4H ,4H TRR,4H ,4H
5 ,4H TZZ,4H ,4H ,4H TOD,4H ,4H ,4H TRZ,4H ,4H
6,4HTIME,4H ,4H ,4H DT,4H ,4H VI,4HSCDS,4HITY ,4HMAGN,4H
7 FLD,4H R ,4HMAGN,4H FLD,4H Z ,4H CUR,4HRENT,4H-R ,4H CUR,4HREN
8T,4H-Z ,4H C,4HP/CV,4H ,4H CON,4HD EL,4HECTR,4H ,4H ,4
9H ,4HTEMP,4HERAT,4HURE ,4HSP H,4HEAT ,4HVOL ,4H POT,4HENTI,4HAL
C                                                    3702
C                                                    3703
C                                                    3704
C                                                    3705
C                                                    3706
C                                                    3707
C                                                    3708
C                                                    3709
C                                                    3710
C                                                    3711

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TUB=T*10.**3 3776
CALL SYMBOL (3.8,9.,.1,11HTIME (MSEC),0.,11) 3777
CALL NUMBER (6.5,9.,.1,TUB,0.,5) 3778
CALL SYMBOL (4.2,8.65,.1,5HCYCLE,0.,5) 3779
CYCLE=NCYCLE 3780
CALL NUMBER (5.2,8.65,.1,CYCLE,0.,-1) 3781
30 CONTINUE 3782
YB=10.**12 3783
XL=10.**12 3784
C ***** 3785
C SEARCHING FOR MAXIMUM AND MINIMUM 3786
C ***** 3787
YT=-10.**12 3788
XR=-10.**12 3789
C ***** 3790
C DETERMINING ORDER OF PLOTTING VARIABLES 3791
C ***** 3792
DO 40 J=1,ILIP 3793
IF (X(J).LT.XL) XL=X(J) 3794
IF (X(J).GT.XR) XR=X(J) 3795
IF (Y(J).LT.YB) YB=Y(J) 3796
IF (Y(J).GT.YT) YT=Y(J) 3797
40 CONTINUE 3798
C ***** 3799
C SCALING NUMBERS AND RE-WRITING IN EXPONENT FORM 3800
C ***** 3801
YT=YB+(YT-YB)*1.2 3802
IF (IHIST.EQ.0) XL=ZLOW 3803
IF (IHIST.EQ.0) XR=ZHIG 3804
YT=YT+1.5*(YT-YB) 3805
ICEX1=0 3806
ICEX2=0 3807
W1=0. 3808
W2=0. 3809
W3=0. 3810
W4=0. 3811
XXLL=ABS(XL) 3812
XXRR=ABS(XR) 3813
YYBB=ABS(YB) 3814
YYTT=ABS(YT) 3815
IF (XR.GT.1.) W1=ALOG10(XR) 3816
IF (YT.GT.1.) W3=ALOG10(YT) 3817
IF (XL.LT.-1.) W2=ALOG10(XXLL) 3818
IF (YB.LT.-1.) W4=ALOG10(YYBB) 3819
IF (XR.GT.-1..AND.XR.LT.1..AND.XR.NE.0.) W1=-ALOG10(1./XXRR) 3820
IF (YT.GT.-1..AND.YT.LT.1..AND.YT.NE.0.) W3=-ALOG10(1./YYTT) 3821
IF (XL.GT.-1..AND.XL.LT.1..AND.XL.NE.0.) W2=-ALOG10(1./XXLL) 3822
IF (YB.GT.-1..AND.YB.LT.1..AND.YB.NE.0.) W4=-ALOG10(1./YYBB) 3823
ICEX1=-W1 3824
ICEX2=-W3 3825
IF (W1.GT.0..AND.W2.GT.0..AND.W2.GT.W1) ICEX1=-W2 3826
IF (W3.GT.0..AND.W4.GT.0..AND.W4.GT.W3) ICEX2=-W4 3827
IF (W1.LT.0..AND.W2.LT.0..AND.W1.LT.W2) ICEX1=-W2 3828
IF (W3.LT.0..AND.W4.LT.0..AND.W3.LT.W4) ICEX2=-W4 3829
YB=YB*10.**ICEX2 3830
YT=YT*10.**ICEX2 3831
XL=XL*10.**ICEX1 3832
XR=XR*10.**ICEX1 3833
DO 50 KG=1,ILIP 3834
X(KG)=X(KG)*10.**ICEX1 3835
Y(KG)=Y(KG)*10.**ICEX2 3836
50 CONTINUE 3837
IE=IE+ICEX 3838
C ***** 3839

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C	WARNING ABOUT VARIABLES OF CONSTANT VALUE	3840
C	*****	3841
	IF (XR.NE.XL.AND.YB.NE.YT) GO TO 60	3842
	CALL SYMBOL (3.,6.5.,1,12HND CHANGE IN,0.,12)	3843
	CALL SYMBOL (5.2,6.5.,1,TLAB(1,1),0.,4)	3844
	CALL SYMBOL (5.60,6.5.,1,TLAB(1,2),0.,4)	3845
	CALL SYMBOL (6.00,6.5.,1,TLAB(1,3),0.,4)	3846
	IF (JZ.EQ.21) CALL SYMBOL (3.,5.,1,12HI= J= ,0.,12)	3847
	CALL NUMBER (2.5,3.,1,YB,0.,2)	3848
	CALL NUMBER (5.0,3.,1,YT,0.,2)	3849
	CALL SYMBOL (8.,3.,1,TLOB(JCODE),0.,4)	3850
	CALL SYMBOL (8.40,3.,1,TLOB(JCODE+1),0.,4)	3851
	CALL SYMBOL (8.80,3.,1,TLOB(JCODE+2),0.,4)	3852
	IF (JZ.EQ.21) CALL NUMBER (3.4,4.8.,1,CIPLOT,0.,-1)	3853
	IF (JZ.EQ.21) CALL NUMBER (4.2,4.8.,1,CJPLOT,0.,-1)	3854
60	CONTINUE	3855
C	*****	3856
C	SETTING UP INTERVALS	3857
C	*****	3858
	IF (XR.EQ.XL.OR.YB.EQ.YT) RETURN	3859
	DELT=(XR-XL)/10.	3860
	CALL TRUN (DELT,DELTA)	3861
	IM=XL/DELTA	3862
	CM=IM	3863
	IF (XL.GT.0.) XL=CM*DELTA	3864
	IF (XL.LT.0.) XL=(CM-1.)*DELTA	3865
	DX=DELTA	3866
	DELT=(YT-YB)/10.	3867
	CALL TRUN (DELT,DELTA)	3868
	IF (DELTA.EQ.0.) RETURN	3869
	IM=YB/DELTA	3870
	CM=IM	3871
	IF (YB.GT.0.) YB=CM*DELTA	3872
	IF (YB.LT.0.) YB=(CM-1.)*DELTA	3873
	IF (XL.EQ.XR.OR.YB.EQ.YT) RETURN	3874
	DY=DELTA	3875
	CALL NXVDSB (1,XL,XR,-1)	3876
	CALL NXVDSB (2,YB,YT,-1)	3877
	CALL CHSIZV (3,3)	3878
	CALL DXDYV (1,XL,XR,DX,N,I,NX,DC,IERR)	3879
	CALL DXDYV (2,YB,YT,DY,M,J,NY,DC,IERR)	3880
	LX=2	3881
	LY=2	3882
C	*****	3883
C	SETTING GRIDS	3884
C	*****	3885
	CALL SETGRD (XL,XR,YB,YT,DX,DY,LX,LY)	3886
	DD 80 J=2, ILIP	3887
	M1=0	3888
	M2=0	3889
	M3=0	3890
	M4=0	3891
	CALL NXVDSB (3,X(J-1),A3,M1)	3892
	CALL NXVDSB (4,Y(J-1),A3,M2)	3893
	CALL NXVDSB (3,X(J),A3,M3)	3894
	CALL NXVDSB (4,Y(J),A3,M4)	3895
	IF (M1.EQ.M3) Y(J)=Y(J-1)	3896
	DD 70 LV=1,2	3897
	X3=M3/102.3	3898
	X4=M4/102.3	3899
	IF (MFR.EQ.1.AND.MOD(J,5).EQ.0) CALL SYMBOL (X3,X4.,1,SYMB(ICODE),	3900
	10.,1)	3901
	CALL LINEV (M1,M2,M3,M4)	3902
70	CONTINUE	3903

80	CONTINUE	3904
	IF (ICD.EQ.0) RETURN	3905
	DO 130 KX=1,2	3906
	WRITE (6,160) (TITLE(I),I=1,15)	3907
	DO 85 KW=1,15	3908
	XCD=2.+KW*.70	3909
85	CALL SYMBOL (XCD,9.5,.2,TITLE(KW),0.,.4)	3910
C	*****	3911
C	PRINTING VARIABLE NAMES AND DIMENSIONS	3912
C	*****	3913
	DO 120 MK=1,2	3914
	DO 110 K=1,3	3915
	JK=JCODE-1+K	3916
	C1=K-1	3917
	CX=C1*.40+3.5	3918
	CY1=C1*.40+4.2	3919
	CY2=C1*.40+5.2	3920
	CZ=C1*.40+5.5	3921
	IF (MK.EQ.2) CZ=0.22	3922
	IF (MFR.EQ.0) GO TO 100	3923
	ICZ=22+(IKT-1)*12	3924
	CZ=ICZ	3925
	CZ=CZ/100.	3926
100	IF (MK.EQ.1) CALL SYMBOL (CX,.3,.1,TLAB(3,K),0.,.4)	3927
	IF (MK.EQ.1) CALL SYMBOL (CZ,.3,.1,TLAB(2,K),0.,.4)	3928
	IF (MK.EQ.2) CALL SYMBOL (CZ,CY1,.1,TLABEL(JK),90.,.4)	3929
	IF (MK.EQ.2) CALL SYMBOL (CZ,CY2,.1,TLDB(JK),90.,.4)	3930
110	CONTINUE	3931
C	*****	3932
C	PRINTING ORDER OF VARIABLES (1ST,2ND,3RD,ETC..) TO BE PLOTTED	3933
C	*****	3934
	IX=32+(IKT-1)*12	3935
	IF (MFR.EQ.0) IX=50	3936
	CIX=IX	3937
	CIX=CIX/100.	3938
	IF (MK.EQ.2) CALL SYMBOL (CIX,5.5,.1,1HE,90.,1)	3939
	IF (MK.EQ.1) CALL SYMBOL (5.00,.2,.1,1HE,0.,1)	3940
	CDUMB=10.**(ICEX2)	3941
	IF (MK.EQ.1) CALL NUMBER (5.25,.2,.1,CDUMB,0.,-1)	3942
	CDUMB=10.**(ICEX1)	3943
	IF (MK.EQ.2) CALL NUMBER (CIX,5.25,.1,CDUMB,90.,-1)	3944
120	CONTINUE	3945
	CALL CHSIZV (3,3)	3946
C	*****	3947
C	CELL IDENTIFICATION	3948
C	*****	3949
	IF (MDIM.EQ.1,DR.MDIM.EQ.2) GO TO 130	3950
	CALL SYMBOL (4.,9.,.1,21H I= J= ,0.,21)	3951
	CALL NUMBER (4.48,9.,.1,CIPLOT,0.,-1)	3952
	CALL NUMBER (5.40,9.,.1,CJPLD,0.,-1)	3953
130	CONTINUE	3954
	IF (MFR.EQ.0) GO TO 150	3955
	YK=800-IKT*20	3956
	IK=YK	3957
	CY=YK/102.3	3958
	DO 140 K=1,3	3959
	JK=ICD	3960
	JK=3*(JK-3)+K	3961
	CX1=K-1	3962
	CX2=CX1*.40+8.	3963
	CALL SYMBOL (CX2,CY,.1,TLDB(JK),0.,.4)	3964
	CALL SYMBOL (9.4,CY,.1,SYMB(ICD),0.,.1)	3965
140	CONTINUE	3966
150	CONTINUE	3967

```

RETURN 3968
C 3969
C 3970
160 FORMAT (2X,15A4) 3971
END 3972
SUBROUTINE SETGRD (XL,HORZ,YB,VERT,DX,DY,LX,LY) 3973
C 3974
C 3975
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 3976
C SETTING GRID FOR TIME AND SPACE HISTORIES 3977
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 3978
C 3979
C 3980
COMMON /P1/ XGRAPH(25),ZGRAPH(75),XVELT(25,75),ZVELT(25,75),SH(25, 3981
175),DR(25),DZ(75),NOLIN1(25,75),NOLIN2(25,75),ILOW,IHIGH,JLOW,JHIG 3982
2H,XLOW,XHIGH,ZLOW,ZHIGH,ML(10),MDIM(10),NCYCLE,ISC,DMN(525),XLF(75 3983
3),YLF(75),IPLW,IPHIGH,JPLW,JPHIGH,XPT(50,11),YPT(50,11) 3984
COMMON /P2/ L1,L2,L3,L4,MFRAME(10,2),IPARAM,IRMIN(10),IRMAX(10),JR 3985
1MIN(10),JRMX(10),MPDDE(10),IPAR(10),IKT,IKM,MFR,IPART,NPTS,KLOG 3986
COMMON /P3/ ZZ,L11,L12,L13,L14,E1,E2,E3,E4,ISYM,KL1,KL2,KL3,KL4,PL 3987
10,IHMIN(20),IHMAX(20),JHMIN(20),JHMAX(20),MCDDE(20),IHIST,ICHECK,M 3988
2DVI,IDEI,IVEL,RPV,ILINE,MZDDE(20),IDN(3),ISPAT,IZMIN(20),IZMAX(20 3989
3),JZMIN(20),JZMAX(20),DUMVAR(40),WW,IVX,IVZ,INUMM 3990
C 3991
C 3992
DIMENSION XLAB(50),YLAB(50),IRASX(50),IRASY(50) 3993
C 3994
C 3995
CALL LINEV (100,100,100,100) 3996
CALL LINEV (100,100,100,1000) 3997
NTX=(HORZ-XL)/DX+1. 3998
NTY=(VERT-YB)/DY+1. 3999
XLAB(1)=XL 4000
C ***** 4001
C DEFINING LABELS 4002
C ***** 4003
DD 10 I=2,NTX 4004
10 XLAB(I)=XLAB(I-1)+DX 4005
YLAB(1)=YB 4006
DD 20 I=2,NTY 4007
20 YLAB(I)=YLAB(I-1)+DY 4008
DD 30 I=1,NTX 4009
CALL NXVDSB (3,XLAB(I),T,M1) 4010
30 IRASX(I)=M1 4011
DD 40 I=1,NTY 4012
CALL NXVDSB (4,YLAB(I),T,M2) 4013
40 IRASY(I)=M2 4014
IF (MFR,NE,0) GO TO 60 4015
DD 45 I=1,NTX,LX 4016
CALL LINEV (IRASX(I),100,IRASX(I),150) 4017
45 CONTINUE 4018
DD 50 I=1,NTY,LY 4019
CALL LINEV (100,IRASY(I),150,IRASY(I)) 4020
50 CONTINUE 4021
C ***** 4022
C LABELLING ABSCISSA 4023
C ***** 4024
60 CONTINUE 4025
LOX=LX 4026
IF (NTX.GT.12) LOX=2 4027
DD 70 I=1,NTX,LOX 4028
IRASX(I)=IRASX(I)-24 4029
X1=IRASX(I)/102.3 4030
Y1=70./102.3 4031

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CNB=0.12 4032
NUMB=5 4033
IF (IHIST.GT.0.DR.ISPAT.GT.0) NUMB=2 4034
IF (IHIST.GT.0.DR.ISPAT.GT.0) CNB=0.08 4035
70 CALL NUMBER (X1,Y1,CNB,XLAB(I),0.,NUMB) 4036
C ***** 4037
C LABELLING ORDINATE 4038
C ***** 4039
DO 100 I=1,NTY,LY 4040
ISIG=0 4041
IF (IRASY(I).GT.430.AND.IRASYS(I).LT.640) ISIG=1 4042
DO 100 KIJ=1,2 4043
X1=10./102.3 4044
Y1=IRASY(I)/102.3 4045
IF (MFR.NE.0) GO TO 80 4046
IF (ISIG.EQ.0) CALL NUMBER (X1,Y1,.12,YLAB(I),0.,4) 4047
IF (MFR.EQ.0) GO TO 90 4048
80 ICX=10 4049
ICY=IRASY(I) 4050
ICX=ICX+12*IKT 4051
X1=ICX/102.3 4052
IF (ISIG.EQ.0) CALL NUMBER (X1,Y1,.12,YLAB(I),90.,2) 4053
90 CONTINUE 4054
100 CONTINUE 4055
RETURN 4056
C 4057
C 4058
END 4059
SUBROUTINE NXVDSB (INXV,X1,X2,I1) 4060
C 4061
C 4062
C ***** 4063
C SETTING SCALES 4064
C ***** 4065
C 4066
C 4067
GO TO (10,20,30,40), INXV 4068
10 XMIN=X1 4069
XMAX=X2 4070
GO TO 50 4071
20 YMIN=X1 4072
YMAX=X2 4073
GO TO 50 4074
30 I3=900-150 4075
A3=I3 4076
A4=150. 4077
A1=(X1-XMIN)*A3/(XMAX-XMIN)+A4 4078
I1=A1 4079
GO TO 50 4080
40 I3=900-150 4081
A3=I3 4082
A4=150 4083
A1=(X1-YMIN)*A3/(YMAX-YMIN)+A4 4084
I1=A1 4085
50 RETURN 4086
END 4087
SUBROUTINE TRUN (XIN,YOUT) 4088
C 4089
C 4090
C ***** 4091
C TRUNCATES A NUMBER 4092
C ***** 4093
C 4094
C 4095

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YOUT=0. 4096
IF (XIN.EQ.0.) RETURN 4097
J=1 4098
Y=ABS(XIN) 4099
IF (Y.GT.1.) J=-1 4100
I=0 4101
10 I=I+1 4102
IF (I.GT.50) RETURN 4103
JI=I*J 4104
YI=Y*10.**JI 4105
IF (J.EQ.-1.AND.YI.GT.1.) GO TO 10 4106
IF (J.EQ.1.AND.YI.LT.1.) GO TO 10 4107
IF (J.GT.0) ITRUNC=YI 4108
IF (J.LT.0) ITRUNC=YI*10. 4109
YI=ITRUNC 4110
IF (J.GT.0) IE=-JI 4111
IF (J.LT.0) IE=-JI+J 4112
YOUT=YI*10.**IE*ABS(XIN)/XIN 4113
RETURN 4114
END 4115
SUBROUTINE ARROW (IZC,IXC,M1,M2,XCOMP,ZCOMP) 4116
C 4117
C 4118
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 4119
C DRAWS ARROW FOR VECTOR PLOT 4120
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 4121
C 4122
C 4123
IF (ZCOMP.EQ.0.) ZCOMP=10.**(-6) 4124
VR=ABS(XCOMP/ZCOMP) 4125
VR=ATAN(VR) 4126
IF (ZCOMP.GT.0.) THETA=SIGN(1.,XCOMP)*VR 4127
IF (ZCOMP.LT.0.) THETA=3.1416-SIGN(1.,XCOMP)*VR 4128
THETA1=THETA+150./360.*6.28 4129
THETA2=THETA+210./360.*6.28 4130
XCOORD=M1 4131
YCOORD=M2 4132
X=IZC 4133
Y=IXC 4134
RCOMP=SQRT(ZCOMP**2+XCOMP**2) 4135
RCOMP=RCOMP/2. 4136
X1=X+COS(THETA1)*RCOMP/4. 4137
X2=X+COS(THETA2)*RCOMP/4. 4138
Y1=Y+SIN(THETA1)*RCOMP/4. 4139
Y2=Y+SIN(THETA2)*RCOMP/4. 4140
IX1=X1 4141
IX2=X2 4142
IY1=Y1 4143
IY2=Y2 4144
CALL LINEV (IZC,IXC,IX1,IY1) 4145
CALL LINEV (IZC,IXC,IX2,IY2) 4146
CALL LINEV (IX1,IY1,IX2,IY2) 4147
RETURN 4148
END 4149
SUBROUTINE PARTCL 4150
C 4151
C 4152
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 4153
C DRAWS PARTICLES 4154
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 4155
C 4156
C 4157
COMMON /TPLT/ TPLTMI,TPLTMA,TPLTDE,TPLTDL,TZERO,T 4158
COMMON /CMESH/ KMAX,JMAX,KP1,JP1,KP2,JP2 4159

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COMMON/P1/R (45),Z (225),V (45,225),U (45,225), 4160
1SH(45,225),FR(45),FZ(225),NOLIN1(45,225),NOLIN2(45,225),ILOW, 4161
IHIGH,JLOW,JHIGH,XLOW,XHIGH,ZLOW,ZHIGH,ML(10),MDIM(10),NCYCLE,ISC, 4162
2DMN(525),XLF(225),YLF(225),IPLW,IPHIGH,JPLW,JPHIGH,XPT(50,11), 4163
3YPT(50,11) 4164
COMMON /P3/ ZZ,L11,L12,L13,L14,E1,E2,E3,E4,ISYM,KL1,KL2,KL3,KL4,PL 4165
1D,IHMIN(20),IHMAX(20),JHMIN(20),JHMAX(20),MCODE(20),IHIST,ICHECK,M 4166
2DVE,1DET,IVEL,RPV,ILINE,MZODE(20),IDN(3),1SPAT,IZMIN(20),IZMAX(20) 4167
3),JZMIN(20),JZMAX(20),DUMVAR(40),WW,IVX,IVZ,INUMM 4168
DATA CKT/O./ 4169
C 4170
C 4171
X1=Z(1) 4172
C ***** 4173
C DETERMINING SIZE OF POINT TO BE PLOTTED 4174
C ***** 4175
X2=Z(2) 4176
CALL NXVDSB (3,X1,S,NX1) 4177
CALL NXVDSB (3,X2,S,NX2) 4178
NDIF=IABS(NX2-NX1) 4179
CPT=NDIF 4180
CPT=CPT*1.0/102.3 4181
IF (CPT.GT.1..OR.CPT.LT..01) CPT=0.25 4182
DKT=1. 4183
IF (ISYM.GT.0.AND.CKT.GT.0.) DKT=0.5 4184
CKT=CKT+DKT 4185
IKT=CKT 4186
IF (IKT.EQ.1) TLOW=TPLTMI 4187
DT=T-TLOW 4188
TLOW=T 4189
C ***** 4190
C DEFINING THE LOCATION OF A NEW SET OF TRACER PARTICLES 4191
C ***** 4192
IF (DT.LE.0.) RETURN 4193
IF (IKT.GT.NPTS) GO TO 20 4194
K=0 4195
DO 10 M=IPLW,IPHIGH 4196
DO 10 L=JPLW,JPHIGH 4197
IF (IPLW.NE.IPHIGH) K=M 4198
IF (JPLW.NE.JPHIGH) K=L 4199
XPT(K,IKT)=Z(L) 4200
YPT(K,IKT)=R(M) 4201
10 CONTINUE 4202
KK=K 4203
20 CONTINUE 4204
C ***** 4205
C REDEFINING LOCATION OF TRACER PARTICLES 4206
C ***** 4207
IF (IKT.GT.NPTS) IKT=NPTS 4208
IF (IKT.GE.10) IKT=10 4209
DO 30 M=2,IKT 4210
DO 30 L1=IPLW,IPHIGH 4211
DO 30 L2=JPLW,JPHIGH 4212
IF (IPLW.NE.IPHIGH) K=L1 4213
IF (JPLW.NE.JPHIGH) K=L2 4214
X=XPT(K,M) 4215
Y=YPT(K,M) 4216
XL=X 4217
YL=Y 4218
IF (ISYM.EQ.1) XL=ABS(XL) 4219
IF (ISYM.EQ.2) YL=ABS(YL) 4220
CALL CELL (XL,YL,II,JJ) 4221
JP=JJ+1 4222
IF (X.LE.Z(JJ).AND.JJ.GT.1) JP=JJ-1 4223

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IP=II+1
RR=R(II)
IF (Y.LE.RR.AND.II.GT.1) IP=II-1
DZ=Z(JJ+1)-Z(JJ)
DR=R(II+1)-R(II)
VEL1X=U(II,JJ)+(X-Z(JJ))/DZ*(U(IP,JJ)-U(II,JJ))
VEL2X=U(II,JP)+(X-Z(JJ))/DZ*(U(IP,JP)-U(II,JP))
VEL1Y=V(II,JJ)+(Y-RR)/DR*(V(IP,JJ)-V(II,JJ))
VEL2Y=V(IP,JJ)+(Y-RR)/DR*(V(IP,JP)-V(IP,JJ))
XPT(K,M)=XPT(K,M)+(VEL1X+(X-Z(JJ))/DZ*(VEL2X-VEL1X))*DT
YPT(K,M)=YPT(K,M)+(VEL1Y+(Y-RR)/DR*(VEL2Y-VEL1Y))*DT
30 CONTINUE
C *****
C PLOTTING TRACER PARTICLES
C *****
MLOW=JPLDW
IF (IPLDW.NE.IPHIGH) MLOW=IPLDW
DO 40 M=MLOW,KK
DO 40 J=2,IKT
X=XPT(M,J)
Y=YPT(M,J)
CALL NXVDSB (3,X,S,N1)
CALL NXVDSB (4,Y,S,N2)
IF (X.GT.Z(JP2).DR.X.LT.Z(1).DR.Y.GT.R(KP2).DR.Y.LT.R(1)) GO TO 40
CALL PLOTV (N1,N2,44)
40 CONTINUE
RETURN
C
END
SUBROUTINE CELL (X,Y,II,JJ)
C
C
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C SELECTS CELL CONTAINING PARTICLES
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C
C
COMMON/P1/R (45),Z (225),XVELT(45,225),ZVELT(45,225),
1SH(45,225),DR(45),DZ(225), NOLIN1(45,225),NOLIN2(45,225),ILDW,
1IHIGH,JLDW,JHIGH,XLOW,XHIGH,ZLOW,ZHIGH,ML(10),MDIM(10),NCYCLE,ISC,
2DMN(525),XLF(225),YLF(225),IPLDW,IPHIGH,JPLDW,JPHIGH,XPT(50,11),
3YPT(50,11)
COMMON /P2/ L1,L2,L3,L4,MFRAME(10,2),IPARAM,IRMIN(10),IRMAX(10),JR
1MIN(10),JRMAX(10),MPDDE(10),IPAR(10),IKT,IKM,MFR,IPART,NPTS,KLOG
COMMON /P3/ ZZ,L11,L12,L13,L14,E1,E2,E3,E4,ISYM,KL1,KL2,KL3,KL4,PL
10,IHMIN(20),IHMAX(20),JHMIN(20),JHMAX(20),MCDDE(20),IHIST,ICHECK,M
2QVIE,IDET,IVEL,RPV,ILINE,MZDDE(20),IDN(3),ISPAT,IZMIN(20),IZMAX(20
3),JZMIN(20),JZMAX(20),DUMVAR(40),WW,IVX,IVZ,INUMM
COMMON /CMESH/ KMAX,JMAX,KP1,JP1,KP2,JP2
C
C
JLD=1
JHIG=JP2
JMID1=0
10 JMID=(JLD+JHIG)/2
IF (JMID1.EQ.JMID) GO TO 30
JMID1=JMID
ZX=Z(JMID)
IF (ISYM.EQ.1) ZX=ABS(ZX)
IF (ZX.GE.X) JHIG=JMID
IF (ZX.LE.X) JLD=JMID
JJ=JMID
GO TO 10
20 IMID1=0

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	ILD=1	4288
	IHIG=KP2	4289
30	IMID=(ILD+IHIG)/2	4290
	IF (IMID1.EQ.IMID) GO TO 40	4291
	IMID1=IMID	4292
	RR=R(IMID)	4293
	IF (ISYM.EQ.2) RR=ABS(RR)	4294
	IF (RR.GE.Y) IHIG=IMID	4295
	IF (RR.LE.Y) ILD=IMID	4296
	II=IMID	4297
	GO TO 30	4298
40	CONTINUE	4299
	RETURN	4300
	END	4301
	SUBROUTINE SHADE (M1,M2,M3,M4,IQ)	4302
C		4303
C		4304
C	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX	4305
C	SHADE OR GREY LEVEL SCALING	4306
C	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX	4307
C		4308
C		4309
	DIMENSION IPATO(16),IPAT1(16),IPAT2(16),IPAT3(16),IPAT4(16),	4310
	IPAT5(16),IPAT6(16),IPAT7(16),IPAT8(16),IPAT9(16)	4311
	DIMENSION XARRAY(4),YARRAY(4)	4312
	DATA IPATO/16*Z0000/	4313
	DATA IPAT1/7*Z0000,Z0100,8*Z0000/	4314
	DATA IPAT2/4*Z0000,Z0800,7*Z0000,Z0010,3*Z0000/	4315
	DATA IPAT3/3*Z0000,Z1010,7*Z0000,Z1010,4*Z0000/	4316
	DATA IPAT4/2*Z0000,Z2020,3*Z0000,Z0202,3*Z0000,Z2020,3*Z0000,Z0202	4317
	1,Z0000/	4318
	DATA IPAT5/2*Z0000,Z2222,Z0000,2*Z0000,Z2222,Z0000,2*Z0000,Z2222,	4319
	1Z0000,2*Z0000,Z2222,Z0000/	4320
	DATA IPAT6/Z8888,Z0000,Z2222,Z0000,Z8888,Z0000,Z2222,Z0000,Z8888,	4321
	1Z0000,Z2222,Z0000,Z8888,Z0000,Z2222,Z0000/	4322
	DATA IPAT7/ZAAAA,Z0000,Z5555,Z0000,ZAAAA,Z0000,Z5555,Z0000,	4323
	1ZAAAA,Z0000,Z5555,Z0000,ZAAAA,Z0000,Z5555,Z0000/	4324
	DATA IPAT8/ZAAAA,Z5555,ZAAAA,Z5555,ZAAAA,Z5555,ZAAAA,Z5555,ZAAAA,Z	4325
	15555,ZAAAA,Z5555,ZAAAA,Z5555,ZAAAA,Z5555/	4326
	DATA IPAT9/16*ZFFFF/	4327
	XARRAY(1)=M1/102.3	4328
	XARRAY(2)=M3/102.3	4329
	XARRAY(3)=M3/102.3	4330
	XARRAY(4)=M1/102.3	4331
	YARRAY(1)=M2/102.3	4332
	YARRAY(2)=M2/102.3	4333
	YARRAY(3)=M4/102.3	4334
	YARRAY(4)=M4/102.3	4335
	IQ=IQ-1	4336
	IF (IQ.GT.9) IQ=9	4337
	IF (IQ.EQ.0) CALL TONE(O.,O.,IPATO,-16)	4338
	IF (IQ.EQ.1) CALL TONE(O.,O.,IPAT1,-16)	4339
	IF (IQ.EQ.2) CALL TONE(O.,O.,IPAT2,-16)	4340
	IF (IQ.EQ.3) CALL TONE(O.,O.,IPAT3,-16)	4341
	IF (IQ.EQ.4) CALL TONE(O.,O.,IPAT4,-16)	4342
	IF (IQ.EQ.5) CALL TONE(O.,O.,IPAT5,-16)	4343
	IF (IQ.EQ.6) CALL TONE(O.,O.,IPAT6,-16)	4344
	IF (IQ.EQ.7) CALL TONE(O.,O.,IPAT7,-16)	4345
	IF (IQ.EQ.8) CALL TONE(O.,O.,IPAT8,-16)	4346
	IF (IQ.EQ.9) CALL TONE(O.,O.,IPAT9,-16)	4347
	CALL TONE(XARRAY,YARRAY,4,1)	4348
	RETURN	4349
	END	4350
	SUBROUTINE LEVEL (T,X,Y,II,JJ,S,LL,KK)	4351

```

C 4352
C 4353
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 4354
C CONTOUR PLOT DEVELOPED BY ARD, ARNOLD AFS, TENN. 4355
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 4356
C 4357
C 4358
C DIMENSION T(I1,JJ), X(I1,JJ), Y(I1,JJ) 4359
C DIMENSION S(KK), LL(KK) 4360
C 4361
C 4362
C IMAX=I1-1 4363
C JMAX=JJ-1 4364
C DO 480 J=1,JMAX 4365
C KR=0 4366
C IF ((J/2)*2.EQ.J) KR=1 4367
C DO 480 III=1,IMAX 4368
C I=III 4369
C IF (KR.EQ.1) I=IMAX+1-III 4370
C ESTABLISH QUADRILATERAL TO BE SEARCHED 4371
C X1=X(I,J) 4372
C X2=X(I+1,J) 4373
C X3=X(I+1,J+1) 4374
C X4=X(I,J+1) 4375
C Y1=Y(I,J) 4376
C Y2=Y(I+1,J) 4377
C Y3=Y(I+1,J+1) 4378
C Y4=Y(I,J+1) 4379
C T1=T(I,J) 4380
C T2=T(I+1,J) 4381
C T3=T(I+1,J+1) 4382
C T4=T(I,J+1) 4383
C DO 480 M=1, KK 4384
C TISO=S(M) 4385
C L=LL(M) 4386
C S1=TISO-T1 4387
C S2=TISO-T2 4388
C S3=TISO-T3 4389
C S4=TISO-T4 4390
C S12=S1*S2 4391
C S23=S2*S3 4392
C S34=S3*S4 4393
C S41=S4*S1 4394
C K=1 4395
C IF (S1) 20,10,20 4396
C 10 K=2 4397
C KL=1 4398
C 20 IF (S2) 40,30,40 4399
C 30 K=K+1 4400
C KL=2 4401
C 40 IF (S3) 60,50,60 4402
C 50 K=K+1 4403
C KL=3 4404
C 60 IF (S4) 80,70,80 4405
C 70 K=K+1 4406
C KL=4 4407
C 80 GO TO (300,90,140,270,270), K 4408
C 90 GO TO (100,110,120,130), KL 4409
C 100 CALL POINT (S23,S34,S2,S3,T4,T3,T2,X1,Y1,X2,Y2,X3,Y3,X4,Y4,L) 4410
C GO TO 480 4411
C 110 CALL POINT (S34,S41,S3,S4,T1,T4,T3,X2,Y2,X3,Y3,X4,Y4,X1,Y1,L) 4412
C GO TO 480 4413
C 120 CALL POINT (S41,S12,S4,S1,T2,T1,T4,X3,Y3,X4,Y4,X1,Y1,X2,Y2,L) 4414
C GO TO 480 4415

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130	CALL POINT (S12, S23, S1, S2, T3, T2, T1, X4, Y4, X1, Y1, X2, Y2, X3, Y3, L)	4416
	GO TO 480	4417
140	KLL=KL-1	4418
	GO TO (150, 170, 200), KLL	4419
150	CALL DRAW (L, X1, Y1, X2, Y2)	4420
	IF (S34.LT.O.) GO TO 160	4421
	GO TO 480	4422
160	TP=S3/(T4-T3)	4423
	PX1=X3+TP*(X4-X3)	4424
	PY1=Y3+TP*(Y4-Y3)	4425
	PX2=TP*(X1-X2)+X2	4426
	PY2=TP*(Y1-Y2)+Y2	4427
	GO TO 470	4428
170	IF (S2.EQ.O.) GO TO 180	4429
	CALL DRAW (L, X1, Y1, X3, Y3)	4430
	GO TO 480	4431
180	CALL DRAW (L, X3, Y3, X2, Y2)	4432
	IF (S41.LT.O.) GO TO 190	4433
	GO TO 480	4434
190	TP=S4/(T1-T4)	4435
	PX1=X4+TP*(X1-X4)	4436
	PY1=Y4+TP*(Y1-Y4)	4437
	PX2=TP*(X2-X3)+X3	4438
	PY2=TP*(Y2-Y3)+Y3	4439
	GO TO 470	4440
200	IF (S2) 220, 210, 220	4441
210	CALL DRAW (L, X2, Y2, X4, Y4)	4442
	GO TO 480	4443
220	IF (S3) 250, 230, 250	4444
230	IF (J.EQ.JMAX) CALL DRAW (L, X3, Y3, X4, Y4)	4445
	IF (S12) 240, 480, 240	4446
240	TP=S1/(T2-T1)	4447
	PX1=X1+TP*(X2-X1)	4448
	PY1=Y1+TP*(Y2-Y1)	4449
	PX2=TP*(X3-X4)+X4	4450
	PY2=TP*(Y3-Y4)+Y4	4451
	GO TO 470	4452
250	IF (I.EQ.1) CALL DRAW (L, X1, Y1, X4, Y4)	4453
	IF (S23) 260, 480, 480	4454
260	TP=S2/(T3-T2)	4455
	PX1=X2+TP*(X3-X2)	4456
	PY1=Y2+TP*(Y3-Y2)	4457
	PX2=TP*(X4-X1)+X1	4458
	PY2=TP*(Y4-Y1)+Y1	4459
	GO TO 470	4460
270	IF (S2.NE.O.O) GO TO 280	4461
	IF (S1.EQ.O.O) CALL DRAW (L, X2, Y2, X1, Y1)	4462
	IF (S3.EQ.O.O) CALL DRAW (L, X2, Y2, X3, Y3)	4463
280	IF (J.NE.JMAX) GO TO 290	4464
	IF (S4.NE.O.O) GO TO 480	4465
	IF (S3.EQ.O.O) CALL DRAW (L, X4, Y4, X3, Y3)	4466
290	IF (I.NE.1) GO TO 480	4467
	IF (S1.EQ.O.O) CALL DRAW (L, X4, Y4, X1, Y1)	4468
	GO TO 480	4469
C	SEARCH P1-P2	4470
300	K=0	4471
	IF (S12) 310, 320, 320	4472
310	TP=S1/(T2-T1)	4473
	K=1	4474
	PX1=X1+TP*(X2-X1)	4475
	PY1=Y1+TP*(Y2-Y1)	4476
C	SEARCH P2-P3	4477
320	IF (S23) 330, 360, 360	4478
330	TP=S2/(T3-T2)	4479

	IF (K) 340, 350, 340	4480
C	CHECK FOR QUADRILATERAL WITH 4 INTERSECTIONS	4481
340	IF (S34, LT. O. O. AND, S41, LT. O. O) GO TO 430	4482
	PX2=X2+TP*(X3-X2)	4483
	PY2=Y2+TP*(Y3-Y2)	4484
	GO TO 470	4485
350	K=K+1	4486
	PX1=X2+TP*(X3-X2)	4487
	PY1=Y2+TP*(Y3-Y2)	4488
C	SEARCH P3-P4	4489
360	IF (S34) 370, 400, 400	4490
370	TP=S3/(T4-T3)	4491
	XP=X4-X3	4492
	YP=Y4-Y3	4493
	IF (K) 380, 390, 380	4494
380	PY2=Y3+TP*YP	4495
	PX2=X3+TP*XP	4496
	GO TO 470	4497
390	K=K+1	4498
	PY1=Y3+TP*YP	4499
	PX1=X3+TP*XP	4500
C	SEARCH P4-P1	4501
400	IF (S41) 410, 480, 480	4502
410	IF (K) 420, 480, 420	4503
420	TP=S4/(T1-T4)	4504
	PX2=X4+TP*(X1-X4)	4505
	PY2=Y4+TP*(Y1-Y4)	4506
	GO TO 470	4507
430	TP=S3/(T4-T3)	4508
	PX2=X3+TP*(X4-X3)	4509
	IF ((PX1-X1)/(X2-X1)-(PX2-X4)/(X3-X4)) 440, 450, 460	4510
440	TP=S4/(T1-T4)	4511
	PX2=X4+TP*(X1-X4)	4512
	PY2=Y4+TP*(Y1-Y4)	4513
	CALL DRAW (L, PX1, PY1, PX2, PY2)	4514
	TP=S2/(T3-T2)	4515
	PX1=X2+TP*(X3-X2)	4516
	PY1=Y2+TP*(Y3-Y2)	4517
	TP=S3/(T4-T3)	4518
	PX2=X3+TP*(X4-X3)	4519
	PY2=Y3+TP*(Y4-Y3)	4520
	GO TO 470	4521
450	PY2=Y3+TP*(Y4-Y3)	4522
	CALL DRAW (L, PX1, PY1, PX2, PY2)	4523
	TP=S2/(T3-T2)	4524
	PX1=X2+TP*(X3-X2)	4525
	PY1=Y2+TP*(Y3-Y2)	4526
	TP=S4/(T1-T4)	4527
	PX2=X4+TP*(X1-X4)	4528
	PY2=Y4+TP*(Y1-Y4)	4529
	GO TO 470	4530
460	TP=S2/(T3-T2)	4531
	PX2=X2+TP*(X3-X2)	4532
	PY2=Y2+TP*(Y3-Y2)	4533
	CALL DRAW (L, PX1, PY1, PX2, PY2)	4534
	TP=S3/(T4-T3)	4535
	PX1=X3+TP*(X4-X3)	4536
	PY1=Y3+TP*(Y4-Y3)	4537
	TP=S4/(T1-T4)	4538
	PX2=X4+TP*(X1-X4)	4539
	PY2=Y4+TP*(Y1-Y4)	4540
470	CALL DRAW (L, PX1, PY1, PX2, PY2)	4541
480	CONTINUE	4542
	RETURN	4543

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END 4544
SUBROUTINE POINT (S23, S34, S2, S3, T4, T3, T2, X1, Y1, X2, Y2, X3, Y3, X4, Y4, L
1) 4545
C 4546
C 4547
C 4548
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 4549
C SETTING UP CONTOURS 4550
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 4551
C 4552
C 4553
KT=1 4554
IF (S23) 10, 20, 20 4555
10 KT=2 4556
TP=S2/(T3-T2) 4557
PX1=X2+TP*(X3-X2) 4558
PY1=Y2+TP*(Y3-Y2) 4559
20 IF (S34) 30, 40, 40 4560
30 TP=S3/(T4-T3) 4561
KT=KT+2 4562
40 GO TO (90, 60, 50, 70), KT 4563
50 PX1=X3+TP*(X4-X3) 4564
PY1=Y3+TP*(Y4-Y3) 4565
60 PX2=X1 4566
PY2=Y1 4567
GO TO 80 4568
70 PX2=X3+TP*(X4-X3) 4569
PY2=Y3+TP*(Y4-Y3) 4570
80 CALL DRAW (L, PX1, PY1, PX2, PY2) 4571
90 RETURN 4572
END 4573
SUBROUTINE DRAW (L, PX1, PY1, PX2, PY2) 4574
C 4575
C 4576
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 4577
C DRAWS CONTOUR 4578
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 4579
C 4580
C 4581
COMMON /MOVE/ XX(4), YY(4) 4582
C 4583
C 4584
I1=PX1*102.3 4585
I2=PY1*102.3 4586
I3=PX2*102.3 4587
I4=PY2*102.3 4588
CALL LINEV (I1, I2, I3, I4) 4589
RETURN 4590
END 4591
SUBROUTINE THREED 4592
C 4593
C 4594
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 4595
C SETS UP THREE-DIMENSIONAL PLOTS 4596
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 4597
C 4598
C 4599
COMMON/P1/XGRAPH(45), ZGRAPH(225), XVELT(45, 225), ZVELT(45, 225), 4600
1SH(45, 225), DR(45), DZ(225), NOLIN1(45, 225), NOLIN2(45, 225), ILOW, 4601
IHIGH, JLOW, JHIGH, XLOW, XHIGH, ZLOW, ZHIGH, ML(10), MDIM(10), NCYCLE, ISC, 4602
2DMN(525), XLF(225), YLF(225), ILOW, IPHIGH, JLOW, JPHIGH, XPT(50, 11), 4603
3YPT(50, 11) 4604
COMMON /P2/ L1, L2, L3, L4, MFRAME(10, 2), IPARAM, IRMIN(10), IRMAX(10), JR 4605
IMIN(10), JRMAX(10), MPODE(10), IPAR(10), IKT, IKM, MFR, IPART, NPTS, KLOG 4606
COMMON /P3/ ZZ, LI1, LI2, LI3, LI4, E1, E2, E3, E4, ISYM, KL1, KL2, KL3, KL4, PL 4607

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10, IHMIN(20), IHMAX(20), JHMIN(20), JHMAX(20), MCODE(20), IHIST, ICHECK, M          4608
2DVIE, IDET, IVEL, RPV, ILINE, MZODE(20), IDN(3), ISPAT, IZMIN(20), IZMAX(20)      4609
3), JZMIN(20), JZMAX(20), DUMVAR(40), WW, IVX, IVZ, INUMM                          4610
COMMON /P4/ MASK(2000), VERTEX(16), XG(45), ZG(225), YY(225), XXG(225),          4611
1ZSH(01,001)                                                                       4612
C                                                                                   4613
C                                                                                   4614
C                                                                                   4615
C *****                                                                    4616
C SETS UP "X, Y, Z" DATA FOR TWO INDIVIDUAL 3-D PLOT PACKAGES                    4617
C *****                                                                    4618
ID3=1                                                                                4619
IHIGH=IHIGH+1                                                                      4620
JHIGH=JHIGH+1                                                                      4621
NRA=IHIGH                                                                           4622
NCA=JHIGH                                                                           4623
IDPT=0                                                                              4624
ICROSS=1                                                                            4625
X1=1                                                                                4626
X2=NRA+1                                                                            4627
Y1=1                                                                                4628
Y2=NCA+1                                                                            4629
SCL=0.5                                                                            4630
C *****                                                                    4631
C PACKAGE "ONE"                                                                    4632
C *****                                                                    4633
CALL FRAMEV(3)                                                                      4634
X0=5.                                                                               4635
Y0=12.                                                                              4636
CN1=45.                                                                             4637
CN2=225.                                                                            4638
DO 10 J=1, JHIGH                                                                    4639
IF (J.GT.1) ZGG=ZGRAPH(J-1)+DZ(J-1)/2.                                           4640
IF (J.EQ.1) ZGG=ZGRAPH(J)-DZ(J)/2.                                               4641
CALL NXVDSB(3, ZGG, T, M1)                                                         4642
ZG(J)=(M1-150)/102.3+1.                                                           4643
10 CONTINUE                                                                         4644
DO 20 I=1, IHIGH                                                                    4645
IF (I.GT.1) XGG=XGRAPH(I-1)+DR(I-1)/2.                                           4646
IF (I.EQ.1) XGG=XGRAPH(I)-DR(I)/2.                                               4647
CALL NXVDSB(4, XGG, T, M1)                                                         4648
XG(I)=(M1-150)/102.3+1.                                                           4649
20 CONTINUE                                                                         4650
KPH=IHIGH                                                                           4651
C *****                                                                    4652
C CROSS-HATCH LINES RUNNING IN ONE DIRECTION                                     4653
C *****                                                                    4654
DO 40 NLINE=1, KPH                                                                  4655
NLINE=NLINE                                                                         4656
XX=XG(NLINE)                                                                        4657
DO 30 NJ=1, JHIGH                                                                    4658
M=NLINE                                                                              4659
N=NJ                                                                                  4660
MM1=M-1                                                                              4661
NM1=N-1                                                                              4662
IF (M.EQ.1) MM1=M                                                                    4663
IF (N.EQ.1) NM1=N                                                                    4664
IF (M.EQ.IHIGH) M=MM1                                                                4665
IF (N.EQ.JHIGH) N=NM1                                                                4666
YY(NJ)=1.                                                                            4667
NPP=0                                                                                4668
IF (NOLINI(M, N).GT.1 .OR. NOLINI(MM1, N).GT.1 .OR. NOLINI(MM1, NM1).GT.1      4669
1 .OR. NOLINI(M, NM1).GT.1) NPP=1                                                 4670
IF (NPP.EQ.0) YY(NJ)=(SH(M, N)+SH(MM1, N)+SH(MM1, NM1)+SH(M, NM1))/4.          4671
1SCL+1.

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30 CONTINUE                                4672
  CALL PLOT3D (0011,XX,YY,ZG,0.,1.,1.,NLINE,JHIGH,CN1,CN2,XO,YO,10.,
  1MASK,0)                                  4673
40 CONTINUE                                4674
C *****                                     4675
C CROSS-HATCH LINES RUNNING IN THE OTHER DIRECTION 4676
C *****                                     4677
C *****                                     4678
  DD 60 NLINE=1,JHIGH                        4679
  ZZ=ZG(NLINE)                               4680
  DD 50 NI=1,KPH                              4681
  NLINE=NI                                    4682
  M=NI                                         4683
  N=NLINE                                      4684
  MMI=M-1                                     4685
  NMI=N-1                                     4686
  IF (M.EQ.1) MMI=M                          4687
  IF (N.EQ.1) NMI=N                          4688
  IF (M.EQ.IHIGH) M=MMI                      4689
  IF (N.EQ.JHIGH) N=NMI                      4690
  YY(NI)=1.                                  4691
  NPP=0                                       4692
  IF (NOLINI(M,N).GT.1.OR.NOLINI(MMI,N).GT.1.OR.NOLINI(MMI,NMI).GT.1
  1.OR.NOLINI(M,NMI).GT.1) NPP=1            4693
  IF (NPP.EQ.0) YY(NI)=(SH(M,N)+SH(MMI,N)+SH(MMI,NMI)+SH(M,NMI))/4.*
  1SCL+1.                                     4694
C ZSH(NI,NLINE)=YY(NI)                       4695
C *****                                     4696
50 CONTINUE                                4697
  CALL PLOT3D (1110,XG,YY,ZZ,1.,1.,0.,NLINE,KPH,CN1,CN2,XO,YO,10.,MA
  1SK,VERTEX)                                4698
60 CONTINUE                                4699
  CALL FRAMER (3,VERTEX,MASK)                4700
  IHIGH=IHIGH-1                              4701
  JHIGH=JHIGH-1                              4702
C *****                                     4703
C *****                                     4704
C *****                                     4705
C *****                                     4706
C *****                                     4707
  IF (ID3.EQ.1) RETURN                       4708
  IVIEW=1                                     4709
  CALL PLTMTX (ZSH,NRA,NCA,IVIEW,1DPT,ICROSS,X1,X2,Y1,Y2) 4710
  RETURN                                      4711
  END                                         4712
  SUBROUTINE PLOT3D (IVXYZ,XDATA,YDATA,ZDATA,XSCALE,YSCALE,ZSCALE,NL
  1INE,NPNTS,PHI,THETA,XREF,YREF,XLENTH,MASK,VERTEX) 4713
C *****                                     4714
C *****                                     4715
C *****                                     4716
C *****                                     4717
C *****                                     4718
C *****                                     4719
C *****                                     4720
C *****                                     4721
  INTEGER HIGH,OLDHI,OLDLOW                  4722
  DIMENSION XDATA(1),YDATA(1),ZDATA(1),MASK(1),VERTEX(1) 4723
  DATA INIT,JVXYZ,SPHI,STHETA/-1,-1,-1.0E70,-1.0E70/ 4724
C *****                                     4725
C *****                                     4726
  IF (NLINE.EQ.0) GO TO 640                  4727
  IF (NLINE.NE.1) GO TO 20                   4728
  PIFI=100.0                                 4729
  NYPI=1090                                  4730
  I=NYPI+100                                4731
  CALL PLOT (0,0,0,0,-3)                     4732
  LIMITX=XLENTH*PIFI+0.5                    4733
  I=LIMITX+LIMITX                            4734
  DD 10 K=1,1                                4735

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MASK(K)=INIT	4736
10 CONTINUE	4737
INIT=-1	4738
INCI=-1	4739
I=0	4740
20 IF (JVXYZ.EQ.IVXYZ) GO TO 70	4741
JVXYZ=IVXYZ	4742
INDZ=1	4743
INDY=1	4744
INDX=1	4745
INDV=1	4746
IF (JVXYZ.LT.1000) GO TO 30	4747
INDV=2	4748
JVXYZ=JVXYZ-1000	4749
30 IF (JVXYZ.LT.100) GO TO 40	4750
INDX=2	4751
JVXYZ=JVXYZ-100	4752
40 IF (JVXYZ.LT.10) GO TO 50	4753
INDY=2	4754
JVXYZ=JVXYZ-10	4755
50 IF (JVXYZ.LT.1) GO TO 60	4756
INDZ=2	4757
60 JVXYZ=IVXYZ	4758
70 IF (PHI.EQ.SPHI.AND.THETA.EQ.STHETA) GO TO 80	4759
SPHI=SIN(.0174533*PHI)	4760
CPHI=COS(.0174533*PHI)	4761
STHETA=SIN(.0174533*THETA)	4762
CTHETA=COS(.0174533*THETA)	4763
A11=CPHI	4764
A13=-SPHI	4765
A21=STHETA*SPHI	4766
A22=CTHETA	4767
A23=STHETA*CPHI	4768
SPHI=PHI	4769
STHETA=THETA	4770
80 INCI=-INCI	4771
IF (I.NE.0) I=NPNTS+1	4772
DD 620 K=1, NPNTS	4773
I=I+INCI	4774
GO TO (90,100), INDX	4775
90 X=XDATA(I)+(I-1)*XSCALE	4776
GO TO 110	4777
100 X=XDATA(I)*XSCALE	4778
110 GO TO (120,130), INDY	4779
120 Y=YDATA(I)+(I-1)*YSCALE	4780
GO TO 140	4781
130 Y=YDATA(I)*YSCALE	4782
140 GO TO (150,160), INDZ	4783
150 Z=ZDATA(I)+(NLIN-1)*ZSCALE	4784
GO TO 170	4785
160 Z=ZDATA(I)*ZSCALE	4786
170 XXX=A11*X+A13*Z+XREF	4787
XX=XXX	4788
IF (XX) 180,190,190	4789
180 IX=FIX(XX*PIPI-0.5)	4790
GO TO 200	4791
190 IX=FIX(XX*PIPI+0.5)	4792
200 CONTINUE	4793
YYY=A21*X+A23*Z+YREF	4794
YY=YYY+A22*Y	4795
IF (YY) 210,220,220	4796
210 IY=FIX(YY*PIPI-0.5)	4797
GO TO 230	4798
220 IY=FIX(YY*PIPI+0.5)	4799

230	CONTINUE	4800
	IF (IX.LE.0) IX=1	4801
	IF (IX.GT.LIMITX) IX=LIMITX	4802
	IF (IY.LT.10) IY=10	4803
	IF (IY.GT.NYPI) IY=NYPI	4804
	IF (K.NE.1) GO TO 310	4805
	LOW=IX+IX	4806
	HIGH=LOW-1	4807
	MLOW=MASK(LOW)	4808
	MHIGH=MASK(HIGH)	4809
	IF (MHIGH-IY) 260,270,240	4810
240	IF (MLOW-IY) 250,290,280	4811
250	LDCOLD=0	4812
	GO TO 300	4813
260	MASK(HIGH)=IY	4814
	IF (MLOW.EQ.-1) MASK(LOW)=IY	4815
270	LDCOLD=+1	4816
	GO TO 300	4817
280	MASK(LOW)=IY	4818
290	LDCOLD=-1	4819
300	G1=IX/100.	4820
	G2=IY/100.	4821
	CALL PLDT (G1,G2,3)	4822
	JX=IX	4823
	JY=IY	4824
	IYREF=IY	4825
	IF (INDV.EQ.1) GO TO 620	4826
	INDEX=INCI+6	4827
	VERTEX(INDEX)=XX	4828
	VERTEX(INDEX+1)=YY	4829
	VERTEX(INDEX+8)=XXX	4830
	VERTEX(INDEX+9)=YYY	4831
	IF (NLINE.NE.1) GO TO 620	4832
	VERTEX(1)=XX	4833
	VERTEX(2)=YY	4834
	VERTEX(9)=XXX	4835
	VERTEX(10)=YYY	4836
	GO TO 620	4837
310	IF (IX.NE.JX) GO TO 320	4838
	JY=IY	4839
	GO TO 370	4840
320	YINC=FLOAT(IY-JY)/ABS(FLOAT(IX-JX))	4841
	INCX=(IX-JX)/IABS(IX-JX)	4842
	YJ=JY	4843
330	JX=JX+INCX	4844
	YJ=YJ+YINC	4845
	IF (YJ) 340,350,350	4846
340	JY=FIX(YJ-0.5)	4847
	GO TO 360	4848
350	JY=FIX(YJ+0.5)	4849
360	CONTINUE	4850
	LOW=JX+JX	4851
	HIGH=LOW-1	4852
	MLOW=MASK(LOW)	4853
	MHIGH=MASK(HIGH)	4854
370	IF (MHIGH-JY) 390,390,380	4855
380	IF (MLOW-JY) 400,410,410	4856
390	LDC=+1	4857
	IF (LDCOLD) 450,460,520	4858
400	LDC=0	4859
	IF (LDCOLD) 430,440,420	4860
410	LDC=-1	4861
	IF (LDCOLD) 600,540,530	4862
420	G1=JX/100.	4863

	G2=MHIGH/100.	4864
	IF (MHIGH.LE.IYREF) CALL PLOT (G1,G2,2)	4865
	GO TO 440	4866
430	G2=MLDW/100.	4867
	IF (MHIGH.GE.IYREF) CALL PLOT (G1,G2,2)	4868
440	G1=JX/100.	4869
	G2=JY/100.	4870
	CALL PLOT (G1,G2,3)	4871
	GO TO 610	4872
450	IF (MLDW-IYREF) 460,470,470	4873
460	IF (MHIGH-IYREF) 490,480,480	4874
470	G1=JX/100.	4875
	G2=MLDW/100.	4876
	CALL PLOT (G1,G2,2)	4877
480	G1=JX/100.	4878
	G2=MHIGH/100.	4879
	CALL PLOT (G1,G2,3)	4880
	GO TO 520	4881
490	IF (MHIGH.EQ.-1) GO TO 520	4882
	OLDHI=HIGH-2*INCX	4883
	IF (MASK(OLDHI)-JY) 510,510,500	4884
500	G1=JX/100.	4885
	G2=JY/100.	4886
	CALL PLOT (G1,G2,3)	4887
	GO TO 520	4888
510	G1=(JX-INCX)/100.	4889
	G2=MASK(OLDHI)/100.	4890
	CALL PLOT (G1,G2,3)	4891
520	MASK(HIGH)=JY	4892
	IF (MLDW.EQ.-1) MASK(LOW)=JY	4893
	G1=JX/100.	4894
	G2=JY/100.	4895
	CALL PLOT (G1,G2,2)	4896
	GO TO 610	4897
530	IF (MHIGH-IYREF) 550,550,540	4898
540	IF (MLDW-IYREF) 560,560,570	4899
550	G1=JX/100.	4900
	G2=MHIGH/100.	4901
	CALL PLOT (G1,G2,2)	4902
560	G1=JX/100.	4903
	G2=MLDW/100.	4904
	CALL PLOT (G1,G2,3)	4905
	GO TO 600	4906
570	OLDLOW=LOW-2*INCX	4907
	IF (MASK(OLDLOW)-JY) 580,590,590	4908
580	G1=JX/100.	4909
	G2=JY/100.	4910
	CALL PLOT (G1,G2,3)	4911
	GO TO 600	4912
590	G1=(JX-INCX)/100.	4913
	G2=MASK(OLDLOW)/100.	4914
	CALL PLOT (G1,G2,3)	4915
600	MASK(LOW)=JY	4916
	G1=JX/100.	4917
	G2=JY/100.	4918
	CALL PLOT (G1,G2,2)	4919
610	IYREF=JY	4920
	LOCOLD=LOC	4921
	IF (JX.NE.IX) GO TO 330	4922
620	CONTINUE	4923
	G1=JX/100.	4924
	G2=JY/100.	4925
	CALL PLOT (G1,G2,3)	4926
	IF (INDV.EQ.1) GO TO 630	4927

```

INDEX=-INCI+6                                4928
VERTEX(INDEX)=XX                              4929
VERTEX(INDEX+1)=YY                            4930
VERTEX(INDEX+8)=XXX                           4931
VERTEX(INDEX+9)=YYY                           4932
IF (NLINE.NE.1) GO TO 630                     4933
VERTEX(3)=XX                                  4934
VERTEX(4)=YY                                  4935
VERTEX(11)=XXX                                 4936
VERTEX(12)=YYY                                 4937
630 I=I-1                                      4938
RETURN                                         4939
640 INIT=0                                     4940
RETURN                                         4941
END                                             4942
SUBROUTINE FRAMER (IHCOR, VERTEX, MASK)       4943
C                                              4944
C                                              4945
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 4946
C DRAWS FRAME ABOUT 3-D PLOT                  4947
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 4948
C                                              4949
C                                              4950
DIMENSION VERTEX(1), MASK(1), ARRAY(14)      4951
I=2*IHCOR                                     4952
IF (I.LT.2) I=2                               4953
IF (I.GT.8) I=8                               4954
ARRAY(1)=VERTEX(I-1)                          4955
ARRAY(8)=VERTEX(I)                            4956
ARRAY(2)=VERTEX(I+7)                          4957
ARRAY(9)=VERTEX(I+8)                          4958
ARRAY(4)=ARRAY(2)                             4959
ARRAY(11)=ARRAY(9)                            4960
ARRAY(6)=ARRAY(2)                             4961
ARRAY(13)=ARRAY(9)                            4962
ARRAY(7)=ARRAY(1)                             4963
ARRAY(14)=ARRAY(8)                            4964
I=I-2                                          4965
IF (I.EQ.0) I=8                               4966
ARRAY(3)=VERTEX(I+7)                          4967
ARRAY(10)=VERTEX(I+8)                         4968
I=I+4                                          4969
IF (I.GT.8) I=I-8                             4970
ARRAY(5)=VERTEX(I+7)                          4971
ARRAY(12)=VERTEX(I+8)                         4972
CALL PLOT3D (110, ARRAY, ARRAY(8), 0.0, 1.0, 1.0, 0.0, 2, 7, 0.0, 0.0, 0.0, 0.0, 10.0, 0, MASK, 0) 4973
CALL PLOT (VERTEX(I-1), VERTEX(I), 3)          4975
I=I-2                                          4976
DO 10 J=1, 3                                  4977
I=I+2                                          4978
IF (I.EQ.10) I=2                              4979
CALL PLOT (VERTEX(I+7), VERTEX(I+8), 2)       4980
10 CONTINUE                                    4981
CALL PLOT (VERTEX(I-1), VERTEX(I), 2)         4982
I=I-2                                          4983
IF (I.EQ.0) I=8                               4984
CALL PLOT (VERTEX(I-1), VERTEX(I), 3)         4985
CALL PLOT (VERTEX(I+7), VERTEX(I+8), 2)       4986
RETURN                                         4987
END                                             4988
SUBROUTINE PLMTX (A, NRA, NCA, IVIEW, IOPT, ICROSS, X1, X2, Y1, Y2) 4989
C                                              4990
C THIS IS A 3-D PLOT PACKAGE(2ND) DEVELOPED BY ADTC, EGLIN AFB, FL. 4991

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C
C
C      CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C      THIS IS A GENERAL PURPOSE ROUTINE FOR MAKING AN OBLIQUE PLOT OF
C      A MATRIX OF VALUES.  IT USES PLT3D1 TO ACTUALLY PLOT THE DATA.
C
C      A = INPUT ARRAY TO BE PLOTTED.
C      NRA=NUMBER OF ROWS IN A
C      NCA= NUMBER OF COLUMNS IN A
C      IVIEW INDICATES VIEWING ANGLE
C          = 1, INDICATES VIEW FROM BOTTOM TO TOP
C          = 2, INDICATES VIEW FROM RIGHT TO LEFT
C          = 3, INDICATES VIEW FROM TOP TO BOTTOM
C          = 4, INDICATES VIEW FROM LEFT TO RIGHT
C      IOPT = 0, INDICATES USE DEFAULT SCALING FOR VERTICAL SCALE
C      IOPT = 1, INDICATES VERTICAL SCALE WILL BE SET BY PROGRAMMER (WTO
C      INTERVAL AT WHICH POINTS BETWEEN CURVES WILL BE CONNECTED (USUALL
C      X1 = VARIABLE ASSIGNED TO LAST ROW
C      X2=VARIABLE ASSIGNED TO FIRST ROW
C      Y1= VARIABLE ASSIGNED TO FIRST COLUMN
C      Y2= VARIABLE ASSIGNED TO LAST COLUMN
C          NOTE- IF DO NOT WISH TO ASSIGN VARIABLES, THEN
C          SET X1=NRA, X2=1, Y1=1, Y2=NCA.
C
C      CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C      DIMENSION A(NRA,NCA)
C      COMMON /MAXVAL/ UFDR,UBACK,VLEFT,VRIGHT,WBDT,WTOP,THETA,UAXIS,VAXI
C      IS,UVPLNE,IU(2,2),IV(2,2),IW(2,2),JLAB
C      DIMENSION V(150),W(150)
C      PRINT 160, NRA,NCA,IVIEW,IOPT,ICROSS,X1,X2,Y1,Y2
C      ZMIN=99999999.
C      DX=(X2-X1)/(NRA-1)
C      DY=(Y2-Y1)/(NCA-1)
C      JLAB=0
C      ZMAX=-9999999.
C      DO 10 I=1,NRA
C      DO 10 J=1,NCA
C      ZMAX=AMAX1(ZMAX,A(I,J))
C      ZMIN=AMINI(ZMIN,A(I,J))
10 CONTINUE
C      IF (IVIEW.GT.4.OR.IVIEW.LT.1) IVIEW=1
C      IF (IOPT.EQ.1) GO TO 20
C      WTOP=2.*ZMAX
C      WBDT=ZMIN
C      WBOT=-2.5
C      WTOP=12.5
C      THETA=.7854
20 CONTINUE
C      UVPLNE=WBDT
C      IF (ZMIN.LE.0.AND.ZMAX.GE.0) UVPLNE=0.0
C      CLIPU=99999999.
C      CLIPD=-99999999.
C      XNOISE=0.0
C      GO TO (30,40,50,60), IVIEW
30 UFDR=X2
C      UBACK=X1
C      DELU=-DX
C      DELV=DY
C      VLEFT=Y1
C      VRIGHT=Y2
C      GO TO 70
40 UFDR=Y2

```

UBACK=Y1	5056
DELU=-DY	5057
DELV=-DX	5058
VLEFT=X2	5059
VRIGHT=X1	5060
GO TO 70	5061
50 UFDR=X1	5062
UBACK=X2	5063
DELU=DX	5064
DELV=-DY	5065
VLEFT=Y2	5066
VRIGHT=Y1	5067
GO TO 70	5068
60 UFDR=Y1	5069
DELU=DY	5070
UBACK=Y2	5071
DELV=DX	5072
VLEFT=X1	5073
VRIGHT=X2	5074
70 CONTINUE	5075
UAXIS=VLEFT	5076
VAXIS=UBACK	5077
DO 80 I=1,150	5078
80 W(I)=WBOT	5079
NCURV=ABS((UFDR-UBACK)/DELU)+2.5	5080
NPTS=ABS((VRIGHT-VLEFT)/DELV)+2.5	5081
DO 150 I=1,NCURV	5082
U=UFDR+(I-2.)*DELU	5083
IF (I.EQ.1) U=UFDR	5084
DO 140 J=1,NPTS	5085
V(J)=VLEFT+(J-1.)*DELV	5086
IF (J.EQ.NPTS) V(J)=V(J-1)	5087
IF (I.EQ.1.OR.J.EQ.NPTS) GO TO 140	5088
GO TO (90,100,110,120), IVIEW	5089
90 II=NRA-(I-2)	5090
JJ=J	5091
GO TO 130	5092
100 JJ=NCA-(I-2)	5093
II=NRA-(J-1)	5094
GO TO 130	5095
110 II=I-1	5096
JJ=NCA-(J-1)	5097
GO TO 130	5098
120 JJ=I-1	5099
II=J	5100
130 CONTINUE	5101
C PRINT 9004,NCURV,NPTS,I,J,II,JJ,IVIEW	5102
W(J)=A(II,JJ)	5103
IF (W(J).GT.CLIPU) W(J)=CLIPU	5104
IF (W(J).LT.CLIPD) W(J)=CLIPD	5105
IF (ABS(W(J)).LT.XNOISE) W(J)=XNOISE	5106
140 CONTINUE	5107
IPASS=ICROSS	5108
IF (I.EQ.1) IPASS=-1	5109
CALL PLT3D1 (U,V,W,IPASS,NPTS)	5110
150 CONTINUE	5111
DELW=(WTOP-WBOT)/10.	5112
NLV=(NPTS-1)/15+1	5113
NLU=(NCURV-1)/20+1	5114
CALL PLT3D1 (UBACK,DELW,0.0,-6.1)	5115
CALL PLT3D1 (UBACK,DELU,0.0,-8.NLU)	5116
RETURN	5117
C	5118
160 FORMAT (1X,5I5,4F10.4)	5119

```

END 5120
SUBROUTINE PLT3D1 (UA,VA,WA,IPASS,NPT) 5121
C 5122
C 5123
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 5124
C 3-D PLOT PACKAGE CONTINUED 5125
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX 5126
C 5127
C 5128
COMMON /CLASF/ ICLASS,TITLE(7) 5129
C 5130
C THIS SUBROUTINE WILL MAKE OBLIQUE PLOT OF V VS W FUNCTION FOR 5131
C A GIVEN U. 5132
C 5133
C U= VALUE OF INDEPENDENT VARIABLE U FOR A GIVEN V VS W FUNCTION. 5134
C VA = ONE DIMENSIONAL ARRAY CONTAINING INDEPENDENT VARIABLE V. 5135
C WA=ONE DIMENSIONAL ARRAY CONTAINING DEPENDENT VARIABLE W. 5136
C WA(I)= F(U,VA(I)) 5137
C NPTS= NO. OF PTS IN VA, WA ARRAYS. 5138
C 5139
NOTE : NPTS=IABS(NPT) 5140
IF(NPT.LTO) THEN WA(I)=F(UA(I),VA(I)) 5141
C 5142
IPASS=-1 IF THIS IS FIRST CALL FOR NEW FRAME. 5143
IPASS = -6 DRAW LINES FOR W SCALE AND LABEL W SCALE 5144
VA(1) IS DELTA W FOR LABELING 5145
NPTS = LABEL EVERY NPTS LINE 5146
IPASS = -7 DRAW LINES FOR V SCALE AND LABEL V SCALE 5147
VA(1) IS DELTA V FOR LABELING 5148
NPTS = LABEL EVERY NPTS LINE 5149
IPASS = -8 LABEL U SCALE 5150
VA(1) IS DELTA U FOR LABELING 5151
NPTS = LABEL EVERY NPTS LINE 5152
IPASS = -2 HIDDEN LINES ARE NOT ELIMINATED, 5153
NOT CONNECTED TO PREVIOUS LINE 5154
JLAB IS ALPHA LABEL FOR U SCALE 5155
JLAB = 0 NOT USED FOR THIS CALL 5156
IPASS=N INDICATES EVERY NTH POINT ON THIS CURVE TO NTH POINT OF 5157
PREVIOUS CURVE BE CONNECTED. 5158
C 5159
COMMON /MAXVAL/ UFDR,UBACK,VLEFT,VRIGHT,WBOT,WTOP,THETA,UAXIS,VAXI 5160
IS,UVPLNE,IU(2,2),IV(2,2),IW(2,2),JLAB 5161
C 5162
MAXVAL COMMON IS USED FOR DETERMING SCALES. 5163
UFDR=EXTREME VALUE OF U FOR FOREGROUND. 5164
UBACK= EXTREME VALUE OF U FOR BACKGROUND. 5165
VLEFT= LEFT MOST VALUE OF V. 5166
VRIGHT= RIGHT MOST VALUE OF V 5167
WBOT=MIN VALUE OF W. 5168
WTOP=MAX VALUE OF W 5169
THETA=ANGLE OF OBLIQUE AXIS WITH VERTICAL (RADIAN). NOTE- IF THI 5170
IS ZERO, THEN PLOT WILL BE TWO DIMENSIONAL WITH U AND W AXES CO- 5171
INCIDENT. 5172
UAXIS= VALUE OF V AT WHICH UAXIS IS TO BE DRAWN. 5173
VAXIS= VALUE OF U AT WHICH V AXIS IS TO BE DRAWN. 5174
UVPLNE= VALUE OF W AT WHICH UAXIS AND VAXIS INTERSECT. 5175
C 5176
DIMENSION IXSAV(601), IYSAV(601) 5177
DIMENSION UA(NPT), VA(NPT), WA(NPT) 5178
COMMON MINY(1024),MAXY(1024) 5179
LOGICAL IQUT 5180
C 5181
C 5182
NPTS=IABS(NPT) 5183

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C	PRINT 8880,UFDR,UBACK,VLEFT,VRIGHT,WBOT,WTOP,IPASS,NPTS	5184
C	PRINT 1000, U,(VA(JJ),WA(JJ),JJ=1,NPTS)	5185
	IF (IPASS.GE.0) GO TO 50	5186
	IF (IPASS.EQ.-2) GO TO 50	5187
	IF (IPASS.LE.-6) GO TO 250	5188
C	IF FIRST PASS, ADVANCE FRAME, SET SCALES, AND INITIALIZE MAX AND	5189
C	MIN FUNCTIONS. THE FIRST CURVE TO BE PLOTTED WILL BE THE FARTHEST	5190
C	IN THE FOREGROUND. SUCCEEDING VALUES OF U MUST BE EITHER	5191
C	ASCENDING OR DESCENDING.	5192
C		5193
	CALL FRAMEV (3)	5194
C	FIND SCALE VALUES TO MAKE VARIABLES PROPORTIONAL	5195
	ULNTH=ABS(UFDR-UBACK)	5196
	VLNTH=ABS(VRIGHT-VLEFT)	5197
	WLNTH=ABS(WTOP-WBOT)	5198
	SCMIN=AMINI(ULNTH,VLNTH,WLNTH)	5199
	SCALU=SCMIN/ULNTH	5200
	SCALV=SCMIN/VLNTH	5201
	SCALW=SCMIN/WLNTH	5202
	SCALU=SCALU*22./69.	5203
	IF (IPASS.NE.-3) GO TO 10	5204
	SCALU=1.	5205
	SCALV=1.	5206
	SCALW=1.	5207
10	CONTINUE	5208
	ULNTH=ULNTH*SCALU	5209
	DIFX=ULNTH*SIN(THETA)	5210
	IF (VRIGHT.LT.VLEFT) DIFX=-DIFX	5211
	IF (THETA.GE.0.0) GO TO 20	5212
	XRIGHT=VRIGHT*SCALV	5213
	XLEFT=VLEFT*SCALV+DIFX	5214
	GO TO 30	5215
20	CONTINUE	5216
	XLEFT=VLEFT*SCALV	5217
	XRIGHT=VRIGHT*SCALV+DIFX	5218
30	CONTINUE	5219
	YTOP=(WTOP-WBOT)*SCALW+ULNTH*COS(THETA)+WBOT*SCALW	5220
	YBOT=WBOT*SCALW	5221
	YSCALE=YTOP-YBOT	5222
	XSCALE=ABS(XRIGHT-XLEFT)	5223
	CALL XSCALV (XLEFT,XRIGHT,74,50)	5224
	CALL YSCALV (YBOT,YTOP,50,74)	5225
	DO 40 I=1,1024	5226
	MINY(I)=1000	5227
	MAXY(I)=0	5228
	IF (I.GT.500) GO TO 40	5229
	IXSAV(I)=0	5230
	IYSAV(I)=0	5231
40	CONTINUE	5232
C	CONSTRUCT THE AXES.	5233
C		5234
C	(V AXIS)	5235
	DELU=ABS(VAXIS-UFDR)*SCALU	5236
	DX=DELU*SIN(THETA)	5237
	IDELX=(DX/XSCALE)*900.	5238
	DY=DELU*COS(THETA)	5239
	IDELY=(DY/YSCALE)*900.	5240
	IX1=NXV(VLEFT*SCALV)+IDELX	5241
	IY1=NYV(UVPLNE*SCALW)+IDELY	5242
	IX2=NXV(VRIGHT*SCALV)+IDELX	5243
	IY2=IY1	5244
	CALL LINEV (IX1,IY1,IX2,IY2)	5245
	IV(1,1)=IX1	5246
	IV(2,1)=IY1	5247

	IV(1,2)=IX2	5248
	IV(2,2)=IY2	5249
C		5250
C	(W AXIS)	5251
	IX1=NXV(UAXIS*SCALV)+IDELX	5252
	IX2=IX1	5253
	IY1=NYV(WBOT*SCALW)+IDELY	5254
	IY2=NYV(WTOP*SCALW)+IDELY	5255
	CALL LINEV (IX1,IY1,IX2,IY2)	5256
	IW(1,1)=IX1	5257
	IW(2,1)=IY1	5258
	IW(1,2)=IX2	5259
	IW(2,2)=IY2	5260
C		5261
C	(U AXIS)	5262
C		5263
	IX1=NXV(UAXIS*SCALV)	5264
	IY1=NYV(UVPLNE*SCALW)	5265
	Y2=ULNTH*COS(THETA)+UVPLNE*SCALW	5266
	X2=DIFX+UAXIS*SCALV	5267
	IX2=NXV(X2)	5268
	IY2=NYV(Y2)	5269
	CALL LINEV (IX1,IY1,IX2,IY2)	5270
	IU(1,1)=IX1	5271
	IU(2,1)=IY1	5272
	IU(1,2)=IX2	5273
	IU(2,2)=IY2	5274
C		5275
	50 CONTINUE	5276
	U=UA(1)	5277
	IDUT=.TRUE.	5278
	ICOUNT=ICOUNT+1	5279
	J=NPTS+1	5280
	DO 170 JJ=1,NPTS	5281
	IF (THETA) 60,70,70	5282
	60 J=JJ	5283
	GO TO 80	5284
	70 J=J-1	5285
	80 CONTINUE	5286
	IF (NPT.LT.0.) U=UA(J)	5287
	IF (NPT.GT.0.AND.JJ.GT.1) GO TO 90	5288
	DELU=ABS(U-UFDR)*SCALU	5289
	DX=DELU*SIN(THETA)	5290
	IDELX=(DX/XSCALE)*900.	5291
	DY=DELU*COS(THETA)	5292
	IDELY=(DY/YSCALE)*900.	5293
	90 CONTINUE	5294
	IX2=IXV(VA(J)*SCALV)+IDELX	5295
	IY2=IYV(WA(J)*SCALW)+IDELY	5296
	IF (IPASS.LE.0) GO TO 140	5297
	IF (MOD(J-1,IPASS).NE.0) GO TO 140	5298
	NX=IABS(IX2-IXSAV(J))	5299
	IF (NX.EQ.0) NX=1	5300
	INCX=1	5301
	IF (IXSAV(J).GT.IX2) INCX=-1	5302
	DX=NX	5303
	DY=IY2-IYSAV(J)	5304
	RATIO=DY/DX	5305
	IYST=IYSAV(J)	5306
	IX=IXSAV(J)	5307
	IN=0	5308
	DO 130 I=1,NX	5309
	IX=IX+INCX	5310
	IY=IYST+I*RATIO	5311

IF (IY.LE.MAXY(IX).AND.IY.GE.MINY(IX)) GO TO 100	5312
IN=0	5313
GO TO 120	5314
100 IF (IN.EQ.1.DR.I.EQ.1) GO TO 110	5315
IXCK=IXSAV(J)	5316
IF (IY.GT.MAXY(IX).AND.IYSAV(J).LT.MAXY(IXCK)) IYSAV(J)=MAXY(IXCK)	5317
CALL LINEV (IXSAV(J),IYSAV(J),IX,IY)	5318
110 IXSAV(J)=IX	5319
IYSAV(J)=IY	5320
IN=1	5321
120 CONTINUE	5322
MAXY(IX)=MAXO(IY,MAXY(IX))	5323
MINY(IX)=MINO(IY,MINY(IX))	5324
130 CONTINUE	5325
IF (IN.EQ.0) CALL LINEV (IXSAV(J),IYSAV(J),IX2,IY2)	5326
140 CONTINUE	5327
IF (IPASS.NE.-2) GO TO 160	5328
IF (JJ.EQ.1) GO TO 150	5329
CALL LINEV (IX1,IY1,IX2,IY2)	5330
150 CONTINUE	5331
IX1=IX2	5332
IY1=IY2	5333
IF (JJ.NE.NPTS) GO TO 170	5334
RETURN	5335
160 CONTINUE	5336
IXSAV(J)=IX2	5337
IYSAV(J)=IY2	5338
170 CONTINUE	5339
IX1=IXV(VA(1)*SCALV)+IDELX	5340
IY1=IYV(WA(1)*SCALW)+IDELY	5341
IF (IY1.LT.MAXY(IX1).AND.IY1.GT.MINY(IX1)) IDUT=.FALSE.	5342
DO 230 J=2,NPTS	5343
IX2=IXSAV(J)	5344
IY2=IYSAV(J)	5345
NX=IABS(IX2-IX1)	5346
IF (NX.EQ.0) NX=1	5347
INCX=1	5348
IF (IX2.LT.IX1) INCX=-1	5349
DX=NX	5350
DY=IY2-IY1	5351
RATIO=DY/DX	5352
IX=IX1	5353
IYST=IY1	5354
DO 210 K=1,NX	5355
IX=IX+INCX	5356
IY=IYST+K*RATIO	5357
INDX=IX	5358
MXY=MAXY(INDX)	5359
MNY=MINY(INDX)	5360
IF (IY.LT.MXY.AND.IY.GT.MNY) GO TO 180	5361
IDUT=.TRUE.	5362
GO TO 200	5363
180 CONTINUE	5364
IF (.NOT.IDUT) GO TO 190	5365
CALL LINEV (IX1,IY1,IX,IY)	5366
190 CONTINUE	5367
IDUT=.FALSE.	5368
IX1=IX	5369
IY1=IY	5370
200 CONTINUE	5371
MAXY(INDX)=MAXO(IY,MXY)	5372
MINY(INDX)=MINO(IY,MNY)	5373
210 CONTINUE	5374
IF (.NOT.IDUT) GO TO 220	5375

	CALL LINEV (IX1,IY1,IX2,IY2)	5376
220	CONTINUE	5377
	IND1=IX1	5378
	MAXY(IND1)=MAXO(IY1,MAXY(IND1))	5379
	MINY(IND1)=MINO(IY1,MINY(IND1))	5380
	IX1=IX2	5381
	IY1=IY2	5382
230	CONTINUE	5383
	IF (JLAB.EQ.0) GO TO 240	5384
C	PRINT HDLERITH JLAB	5385
	IXL=IXV(VRIGHT*SCALV)+IDELX+8	5386
	IYL=IDELY+IYV(WBOT*SCALW)	5387
	CALL PRINTV (8,JLAB,IXL,IYL)	5388
	CALL LINE2V (IXL-12,IYL-1,5,0)	5389
	CALL LINE2V (IXL-12,IYL-1,5,0)	5390
240	CONTINUE	5391
	RETURN	5392
250	CONTINUE	5393
	ILAB=0	5394
	IF (IPASS.EQ.-8) GO TO 320	5395
	DELU=ABS(UBACK-UFDR)*SCALU	5396
	DX=DELU*SIN(THETA)	5397
	IDELX=(DX/XSCALE)*900.	5398
	DY=DELU*COS(THETA)	5399
	IDELY=(DY/YSCALE)*900.	5400
	IF (IPASS.EQ.-7) GO TO 280	5401
	DELW=VA(1)	5402
	XD=AMAX1(ABS(WTOP),ABS(WBOT))	5403
	NDL=NDMAX(XD)	5404
	NDIG=MAXO(5,NDL)	5405
	W=WBOT	5406
	IX1=NXV(VLEFT*SCALV)+IDELX	5407
	IX2=NXV(VRIGHT*SCALV)+IDELX	5408
260	IY1=NYV(W*SCALW)+IDELY	5409
	IY2=IY1	5410
	CALL LINEV (IX1,IY1,IX2,IY2)	5411
	IF (MOD(ILAB,NPTS).NE.0) GO TO 270	5412
	CALL LABLV (W,IX1-52,IY1,NDIG,1,NDL)	5413
	CALL LABLV (W,IX1-52,IY1,NDIG,1,NDL)	5414
270	CONTINUE	5415
	ILAB=ILAB+1	5416
	W=W+DELW	5417
	IF (W.GT.WTOP) GO TO 240	5418
	GO TO 260	5419
280	CONTINUE	5420
	DELV=VA(1)	5421
	V=VLEFT	5422
	VR=VRIGHT+.01*(VRIGHT-VLEFT)	5423
290	IX1=NXV(V*SCALV)+IDELX	5424
	IY2=NYV(WTOP*SCALW)+IDELY	5425
	IY1=NYV(WBOT*SCALW)+IDELY	5426
	IX2=IX1	5427
	IX3=IX1-IDELX	5428
	IY3=IY1-IDELY	5429
	CALL LINEV (IX1,IY1,IX2,IY2)	5430
	IF (MOD(ILAB,NPTS).NE.0) GO TO 300	5431
	CALL LABLV (V,IX2-28,IY2+6,NDIG,1,NDL)	5432
	CALL LABLV (V,IX2-28,IY2+6,NDIG,1,NDL)	5433
	CALL LABLV (V,IX3-28,IY3-6,NDIG,1,NDL)	5434
	CALL LABLV (V,IX3-28,IY3-6,NDIG,1,NDL)	5435
300	CONTINUE	5436
	ILAB=ILAB+1	5437
	V=V+DELV	5438
	IF (VRIGHT.GT.VLEFT) GO TO 310	5439

IP=0	5504
IF (I1.EQ.MI3.AND.I2.EQ.MI4) IP=1	5505
X1=I1/102.3	5506
X2=I3/102.3	5507
Y1=I2/102.3	5508
Y2=I4/102.3	5509
IF (IP.EQ.0) CALL PLOT (X1,Y1,+3)	5510
CALL PLOT (X2,Y2,+2)	5511
MI3=I3	5512
MI4=I4	5513
RETURN	5514
END	5515
SUBROUTINE PLOT (A,B,IPL)	5516
COMMON /X1/ IZ	5517
IZ=16	5518
IF (IPL.EQ.999) CALL CLASS (4,3,0,0)	5519
IF (IPL.EQ.999) CALL CALCMP (0.,0.,9999,2)	5520
IF (IPL.EQ.-3) CALL CALCMP (0.,0.,0000,2)	5521
IF (IPL.EQ.2) CALL CALCMP (A,B,IZ,1)	5522
IF (IPL.EQ.3) CALL CALCMP (A,B,0,1)	5523
RETURN	5524
END	5525
SUBROUTINE GSIZE (AA1,AA2,IXX)	5526
LDEV=8	5527
CALL CALCMP (0.,2.,LDEV,0)	5528
CALL CLASS (1,3,0,0)	5529
RETURN	5530
END	5531
SUBROUTINE DXDYV(I1,ALEFT,ARIGHT,DX,I2,I3,I4,I5,I6)	5532
DX=(ARIGHT-ALEFT)/10.	5533
RETURN	5534
END	5535
SUBROUTINE PLOTV(I1,I2,I3)	5536
RETURN	5537
END	5538
SUBROUTINE PRINTV(I1,A,I2,I3)	5539
RETURN	5540
END	5541
SUBROUTINE CHSIZV(I1,I2)	5542
RETURN	5543
END	5544
SUBROUTINE RITE2V(I1,I2,I3,I4,I5,I6,I7,A,I9)	5545
RETURN	5546
END	5547
SUBROUTINE XSCALV(A,B,I1,I2)	5548
RETURN	5549
END	5550
SUBROUTINE YSCALV(A,B,I1,I2)	5551
RETURN	5552
END	5553
SUBROUTINE LABLV(A,I1,I2,I3,I4,I5)	5554
RETURN	5555
END	5556
SUBROUTINE LINE2V(I1,I2,I3,I4)	5557
RETURN	5558
END	5559
FUNCTION IXV(A)	5560
IXV=0	5561
RETURN	5562
END	5563
FUNCTION IYV(A)	5564
IYV=0	5565
RETURN	5566
END	5567

FUNCTION NXV(A)	5568
NXV=0	5569
RETURN	5570
END	5571
FUNCTION NYV(A)	5572
NYV=0	5573
RETURN	5574
END	5575
C/ SRR00894,03,G61K),09999FELDMAN,MSGLEVEL=1,	5576
C/ CLASS=D,REGION=512K,TIME=10	5577
C/ EXEC FTGINCGD,PGMND=SRR00894,OVERLAY=DVLY	5578
C/SYSIN DD *	5579
C*	5580
C/LNK.SYSLIN DD *	5581
C/INCLUDE SYSTFDRT	5582
C/INCLUDE FORTEPDS(SRR00894)	5583
OVERLAY TWO	5584
INSERT DRIVER,INPUT,GEDM,BOUND,DBLQUE,PLATE,SPEC,HULLP1,HULLP2	5585
INSERT TMESTP,CURRNT,OUTPUT,GRAPH,DIGPLT,PRTPLT,EFIELD,BNDPDT,CUR,DFSN	5586
INSERT TEMDIF,VIS,TRID,KSWEAP,JSWEAP,GAMM,SIG,BETA,CP,RGAS,COND,CV	5587
INSERT EDDY,B	5588
INSERT CARRAY,GRAVTY,CTIME,CMATRX,CSTORE,CSTRSS,CMAGN,ETRODE	5589
OVERLAY TWO	5590
INSERT PLOTTE,ROPLT,LABPLT,NXVDSB,LEVEL,POINT,DRAW,TRUN,ARROW,PARTCL	5591
INSERT CELL,PLOT3D,FRAMER,GRIDS,SHADE,THREED,PLTMTX,PLT3D1,NDMAX	5592
INSERT P1,P2,P3,P4	5593
ENTRY MAIN	5594
C*	5595
C/GD.FT08F001 DD UNIT=2400,DISP=(,KEEP),DSN=WPL1,DCB=DEN=2,LABEL=(,BLP)	5596
C/GD.FT14F001 DD UNIT=WRK,SPACE=(CYL,(5,5),RLSE,,ROUND),	5597
C/ DCB=RECFM=VBS	5598
C/GD.FT05F001 DD *	5599
EOB	5600

NOMENCLATURE

Symbol	Description
A	Elliptic equation coefficient/finite difference coefficient
A	Prandtl Mixing Length coefficient
A	Area
B	Elliptic equation coefficient/finite difference coefficient
\bar{B}	Magnetic induction vector
B_r	Radial magnetic induction
B_x	Axial magnetic induction
B_θ	Aximuthal magnetic induction
C	Elliptic equation coefficient/finite difference coefficient
C_s	Shock velocity
c	Speed of sound/electrode thickness
c_p	Specific heat at constant pressure
c_v	Specific heat at constant volume
D	Finite difference coefficient
\bar{E}	Electric field vector
e	Total energy per unit mass
F	Scalar quantity representing ϕ or ψ
F_m	Mass flux
\bar{g}	Gravitational acceleration vector
g_z	Axial gravitational acceleration
g_r	Radial gravitational acceleration
h	Channel width
H_a	Hartmann number

Symbol	Description
I	Current
i	Internal energy per unit mass
\vec{j}	Current vector
j_r	Radial current
j_z	Axial current
K	Load factor
L	Differential operator
M	Mass
M	Mach number
M_r	Radial magnetic flux
M_z	Axial magnetic flux
M_θ	Aximuthal magnetic flux
\hat{n}	Unit vector normal to surface
P	Dimensionless pressure
p	Pressure
\vec{q}	Heat flux vector
r	Radial coordinate
Re	Reynolds number
Re_m	Magnetic Reynolds number
S	Electrode + Insulator thickness
t	Time
T	Temperature
U	Particle velocity
u	Scalar velocity in axial direction
\vec{v}	Velocity vector
v	Scalar velocity in radial direction

Symbol	Description
x	Cartesian coordinate
y	Cartesian coordinate
z	Axial or Cartesian coordinate
α	Coordinate system; Cartesian = (0); axisymmetric = (1)
β	Hall parameter
δ	Boundary layer thickness
γ	Specific heat ratio
ϵ	Integration parameter; explicit = (0); implicit = (1)
ϵ	Strain element
λ_E^2	Prandtl mixing length
λ	Thermal conductivity
λ_t	Thermal conductivity (turbulent)
$\bar{\sigma}$	Electrical conductivity tensor
ρ	Density
σ	Scalar conductivity
σ_+	Scalar conductivity corrected for Hall current
ϕ	Electrical potential
ψ	Current stream function
$\bar{\tau}$	Viscous and/or magneto stress tensor
τ	Stress element
θ	Aximuthal coordinate
μ	Laminar viscosity
μ_E	Eddy viscosity
μ_p	Magnetic permeability
ω	Relaxation Parameter

Symbol	Description
Superscripts	
n	Time cycle
\rightarrow	Vector
\equiv	Tensor
Subscripts	
i	Radial index
j	Axial index
_s	Isentropic
rr	r face, r direction
w	wall
zz	z face, z direction
$\theta\theta$	θ face, θ direction
rz	r face, z direction
∞	Infinity
Mathematical Operators	
$\frac{\partial}{\partial t}$	Partial derivative
$\frac{d}{dt}$	Total derivative
∇	"Del" operator
\cdot	Vector "dot" product
\times	Vector "cross" product
Δ	Finite change